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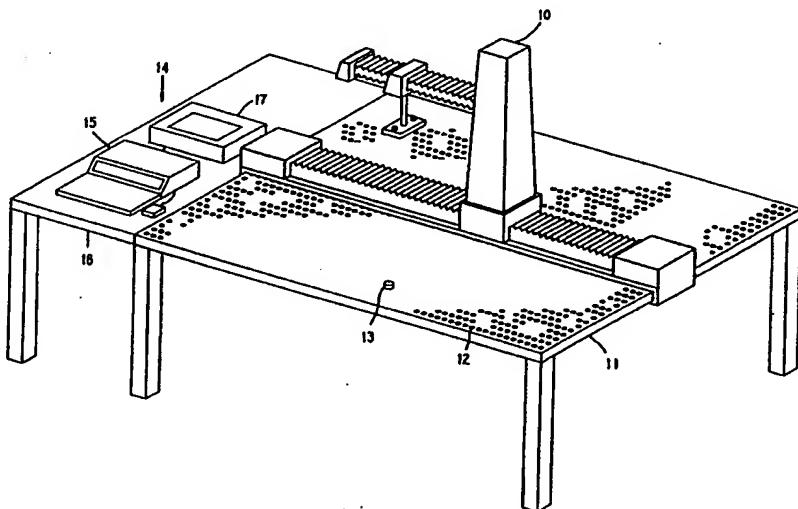
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(54) Title: METHOD AND APPARATUS FOR AUTOMATED TISSUE ASSAY



(57) Abstract

A system which performs a plurality of independent analysis procedures simultaneously, possibly involving differing types of tissues and differing process steps, comprising a robotic arm (10), which may move the different tissue samples among a plurality of processing stations, and a processor (15), which may select the next tissue sample to move, when to move it, and where to move it to. The processor may direct the robotic arm to interleave the differing process steps. The processing stations may be disposed in a set of grid locations (12). The processing stations may comprise workstations (13) for performing individual steps of the tissue assay procedures, such as solution trays. The processor (15) may select a tissue sample to be moved in response to timing information about the procedures. The processor (15) may also optimize the order in which samples are moved to minimize the total time required by the system to complete the procedures.

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DESCRIPTIONMethod and Apparatus for Automated Tissue Assay

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10 Background of the Invention1. Field of the Invention

This invention relates to methods and apparatus useful in automated analysis or testing of tissue samples.

2. Description of Related Art

15 The analysis of tissue is a valuable diagnostic tool used by the pathologist to diagnose many illnesses and by the medical researcher to obtain information about a cell structure.

In order to obtain information from a tissue sample 20 it is usually necessary to perform a number of preliminary operations to prepare the sample for analysis. There are many variations of the procedures to prepare tissue samples for testing. These variations may be considered refinements to adapt the process for individual tissues or 25 because a particular technique is better suited to identify a specific chemical substance or enzyme within the tissue sample. However the basic preparation techniques are essentially the same.

Typically such operations might include the 30 processing of the tissue by fixation, dehydration, infiltration and embedding; mounting of the tissue on a slide and then staining the sample; labeling of the tissue

through the detection of various constituents; grid staining of tissue sections for analysis by an electron microscope or the growing of sample cells in culture dishes.

5       Depending on the analysis or testing to be done, a sample may have to undergo a number of preliminary steps or treatments or procedures before it is ready to be analyzed for its informational content. Typically the procedures are complex and time consuming, involving many  
10      tightly sequenced steps often utilizing expensive and toxic materials.

These procedures must usually be performed in a critical order for each sample and each treatment is frequently time dependent. Additionally the laboratory is  
15      often under extreme pressure to perform many different analysis as soon as possible, entailing many different procedures and tests.

A sample of tissue may undergo an optical microscopic examination so that the relationship of various cells to  
20      each other may be determined or abnormalities may be uncovered. The tissue sample must be an extremely thin strip of tissue so that light may be transmitted therethrough. The average thickness of the tissue sample or slice (often referred to as sections) is in the order  
25      of 2 to 8 micrometers (1 micrometer a 1/1000th of a millimeter). A relatively soft and pliable tissue such as

might come from an organ of the human body, in its fresh state can not be accurately cut into such thin sections.

In addition, in order to see the individual constituents  
30      of the cells, such as the nucleus, the nucleolus, the cytoplasm and the cell membrane, it is preferable to have them colored by different dyes to produce a contrasting appearance between the elements. Very limited dye staining can be done on fresh or recently living tissue  
35      without resorting to chemical processing. Typically a sample of tissue 2.0 to 2.5 square centimeters in area and 3 to 4 millimeters thick is utilized. The tissue sample

is then fixed in a material (a fixative) which not only preserves the cellular structure but also stops any further enzymic action which could result in the petrification or autolysis of the tissue. While many 5 substances can function as a fixative, a four per cent formaldehyde or a ten per cent formalin solution is very common. Other common fixatives would include ethanol, picric acid or mercuric chloride usually with formalin. It should be remembered that in dealing with these 10 substances the containers holding the materials must be suitable. For example mercuric chloride severely corrodes metals and therefor should normally be contained in a glass vessel.

To prepare good samples for microscopic examination 15 the initial step should kill the enzymic processes of the tissue and should alter or denature the proteins of the cell through fixation. The period of fixation may take several hours or even a few days depending upon the tissue type, sample size and type of fixative being used.

20 After fixation, the tissue sample is often dehydrated by the removal of water from the sample through the use of increasing strengths of alcohol or of some other dehydrating fluid. Gradual dehydration is preferred because it causes less distortion to the sample than a 25 rapid dehydration process.

The alcohol is then replaced by a chemical which mixes with wax or some other plastic substance which can permeate the tissue sample and give it a consistency suitable for the preparation of thin sections without 30 disintegration or splitting. Fat solvents, such as chloroform or toluene are commonly used for this step. The sample, which has been dehydrated by the infiltration of alcohol, is next exposed to several changes of solvent over a period that may last from a few hours to days until 35 the alcohol is completely replaced by the solvent. The sample is then exposed to a wax which is soluble in the solvent. If a paraffin type wax is used the infiltration

is at a temperature above its melting point. After the wax infiltration the sample is allowed to cool and the wax solidify so that the sample is entirely embedded in and infiltrated by the wax.

5 A microtome is then utilized to cut thin slices from the tissue sample. The slices are on the order of 5 to 6 micrometers thick. The cut thin sections are floated on water to spread or flatten the section. The section is then disposed on a glass slide usually measuring about 8  
10 by 2.5 millimeters.

The wax is then removed by exposing the sample to a solvent, the solvent removed by alcohol, and the alcohol removed by decreasing the alcoholic concentrations until eventually the tissue is once more infiltrated by water.

15 The infiltration of the sample by water permits the staining of the cell constituents by water soluble dyes.

Prior to the development of automated procedures for the preparation of tissue samples, it often took from two to ten days before the tissue could be examined under a  
20 microscope. In more recent years automated processes have been developed utilizing apparatus to transfer the sample from one fluid to another at defined intervals, and as a result the preparation time has been significantly reduced to 36 to 24 hours.

25 Variations in the materials used in the preparation of the sample are advantageous under some circumstances. The use of ester wax allows sections 1 to 3 micrometers thick to be cut with less contraction than that which occurs when paraffin used. The sample is exposed to  
30 higher temperatures when paraffin wax is used. The use of cellulose nitrate embedding shrinks tissues less than wax, produces good cohesion between tissue layers and permits large undistorted sections to be cut 25 to 30 micrometers thick, if so desired. It is clear that persons with skill  
35 in the art of tissue preparation may use many different materials to which the samples may be exposed.

Tissue staining is a procedure which is utilized to make microscopic structures more visible. Perhaps the most common stain materials are haematoxylin and eosin. Haematoxylin is utilized to clearly stain the nuclei of 5 cells dark blue. Eosin is used to stains the cell cytoplasm various shades of red or yellow, presenting a clear contrast to the blue stain of the nuclei.

Many synthetic dyes are derived from benzene which is colorless but by changing its chemical configuration 10 color compounds are produced which are called chromophores. It is these chromophores which constitute the bulk of the different coloring dyes used in research and routine histology.

There are many techniques by which sample tissues 15 may be stained and most of these techniques require exposing the sample to various solutions. Histochemistry is the science by which chemical reactions are used to identify particular substances in tissues. In addition, many enzymes can be detected by exposing a sample to a 20 particular chemical substance on which the enzyme is known to have an effect such as turning the substance into a colored marker. Thus from the above it can be seen that a sample tissue may be exposed to various antibodies, enzyme labeled detection systems, colormetric substrates, 25 counterstains, washing buffers and organic reagents.

Many experimental and observational research projects involve experimentation to authenticate new techniques and these experiments can be very extensive and time consuming.

30 In addition to the techniques that prepare samples for optical microscopy, techniques often must be utilized which make the use of electron microscopes suitable in the examination of tissue samples. Actually it has been found that the pathological examination of almost any disorder 35 makes electron microscopy highly desirable and often essential.

Tissue samples for use with an electron microscope may be fixed in glutaraldehyde or osmium tetroxide rather than in the standard fixatives used for optical microscopy samples. Usually very small samples of tissue are 5 embedded in methacrylate or epoxy resin and thin sections are cut (about 0.06 micrometers thick). Staining is most often done by colored solutions and not dyes and heavy metal salts are utilized to enhance contrasts of density.

From the above brief description of some of the 10 techniques and materials used by a pathologist in the examination of tissues, it can be seen that for a research laboratory to carry out such a wide variety of processes and numerous different tests assisting apparatus would be desirable and almost mandatory.

15 Many pathology laboratories have in fact automated many of the simple and routine procedures described above such as simple staining or sample embedding. Where the same procedure is repeated with great frequency, laboratories have often designed specialized machines to 20 perform the often repeated testing simultaneously on many samples. Typical of such machines are the equipment used in the routine analysis of blood samples. The equipment used in this type of laboratory is capable of treating multiple samples simultaneously to the same testing 25 procedure, i.e., parallel testing or through the use of multiple machines the same result of parallel testing, is achieved. Alternatively the laboratory may perform the same test repetitively, i.e., sequentially and thus subsequent samples may be subject to a significant time 30 delay.

Research laboratories often are required to perform non-routine analysis requiring many different test procedures. As a result of this lack of repetitive procedures, research laboratories have relatively little 35 automated equipment to assist the researchers in their task. The most obvious reason for this lack of automation is that the equipment presently available is dedicated to

a limited number of procedures most commonly performed. The equipment is not flexible enough to permit a wide variety of operations to be easily accomplished nor does the present equipment permit easy and facile changes to 5 the operations.

Summary of the Invention

The invention provides a system which performs a plurality of independent analysis procedures simultaneously, possibly involving differing types of 10 tissues and differing process steps. The system comprises a robotic arm, which may move the different tissue samples among a plurality of processing stations, and a processor, which may select the next tissue sample to move, when to move it, and where to move it to. In a preferred 15 embodiment, the processor may direct the robotic arm to interleave the differing process steps, for example by time division multiplexing.

In a preferred embodiment, the processing stations may be disposed in a set of grid locations, so that the 20 location of any one processing station may be specified by an X coordinate and a Y coordinate, and possibly a Z coordinate for height. The robotic device may comprise a bench robot with a rotatable tower, with sufficient degrees of freedom that it is able to reach each of the 25 grid locations with suitable movement. The processing stations may comprise workstations for performing individual steps of the tissue assay procedures, such as solution trays, or other equipment useful in bioassay, biomedical or related environments.

30 In a preferred embodiment, the processor may select a tissue sample to be moved in response to timing information about the procedures, which may specify a time range (e.g., a minimum time and maximum time) each process step should take. The processor may determine the exact 35 time for a step by generating a possible sequence of step and examining that sequence for conflicts, adjusting that

sequence in response to those steps with a specified range of times, and iterating the calculation over a plurality of possible sequences. The processor may also optimize the order in which samples are moved to minimize the total 5 time required by the system to complete the procedures for example by generating a plurality of possible sequences, evaluating each sequence for total expected time, and selecting the best sequence available.

In a preferred embodiment, the processor may 10 comprise a graphic interface by which an operator may specify the steps of a procedure. A display of the grid locations may comprise symbols for the workstations, which an operator may identify with a pointing device such as a mouse. The operator may create or edit templates for 15 workstations, create or edit lists of process steps for procedures, monitor the progress of ongoing procedures, or override the determination of what process steps to perform. For example, in a preferred embodiment, the operator may create a list of process steps for a 20 procedure by selecting a sequence of workstations with the mouse, and associating timing or other information for each process step with the selected workstation. The operator may also choose to select a stored list of process steps for a procedure.

25 Thus, the invention provides apparatus and methods whereby a plurality of test procedures can be performed on several samples, e.g., through the use of time division multiplexing. The invention also provides apparatus for use in a laboratory for assisting in the performance of 30 multiple tests which can be easily programmed by the operator to execute sequentially timed step procedures for a plurality of test samples. The invention also provides a flexible laboratory testing system which may use time division multiplexing to interleave the multiple steps of 35 a plurality of test procedures to allow for a plurality of different procedures to be performed on several different test samples in parallel.

Brief Description of the Drawings

Figure 1 shows a robotic device for use with the invention.

Figure 2 shows a laboratory setup having robotic equipment like that shown in figure 1.

Figure 4 is a flowchart showing a time line for five tasks.

Figure 5 is a flowchart illustrating multitasking of the tasks shown in Figure 4.

10 Figure 6 shows a multitask monitoring screen as viewed by an operator.

Figure 7 shows a template building screen as viewed by an operator.

15 Figure 8 shows a process building screen as viewed by an operator.

Figure 9 shows a process timing screen as viewed by an operator.

Description of the Preferred Embodiment

In a preferred embodiment, a multiple axis bench top 20 robot is located to reach peripheral auxiliary equipment disposed in the operational area of the robot. The robot may respond to the output of a PC type computer which utilizes process control programs and assay development software. Peripheral equipment, a plurality of work 25 modules or workstations, is disposed in a grid like pattern around the bench top robot. The workstations maybe disposed or arranged in any convenient pattern and may be represented by a template. Each grid location may contain the necessary equipment to perform the single step 30 of a tissue assay procedure.

For example, a workstation at a grid position may contain a solution tray into which one or more slides may be immersed by the robotic equipment. The slide, or slides, could be immersed to a predetermined depth and 35 retained in the solution tray for a precise time. It should be clear that each grid location may have a

solution tray having different depths or different dimensions. Alternatively, a grid location could contain a slide holder or other peripheral equipment capable of performing a single function on the sample.

- 5        The robotic equipment or robotic arm may be controlled by a standard PC computer. The assay development software is graphic in nature and places a model of the peripheral grid on the screen of the computer. While each tissue assay may have all its steps
- 10      preprogrammed the assay development software permits the steps of the procedure or the timing of the steps to be altered. The graphic nature of the presentation permits laboratory personnel to alter such elements without the necessity of relying on a computer or programming expert.
- 15      The process control software associated with the PC may monitor the progress of the assays, may permit manual override of the of an automatic operation, and most importantly, may permit scheduling of multiple assays simultaneously in parallel through the use of time
- 20      interleaving of the various steps in the test procedures. Thus while sample one may be disposed at workstation in a grid location where it undergoes a drying operation, sample two may be located in a tray containing a staining solution while sample three is undergoing a fixation step.
- 25      The timing of each step is accurate and the system interleaves the steps and utilizes the "waiting" or processing time between steps in a single procedure to perform operational steps on other samples which may be undergoing completely different preparation.

30      Laboratory Bench and Robotic Device

Figure 1 shows a robotic device for use with the invention. Figure 2 shows a laboratory setup having robotic equipment like that shown in figure 1. The equipment may include a robotic device 10 mounted on a

- 35      standard laboratory bench top 11. The bench top 11 defines the operational area reachable by the robotic

device 10. The bench top 11 may have integral therewith a plurality of locating elements such as holes 12. Alternatively, the locating elements may be disposed on a separate base disposed between the robotic device 10 and 5 the laboratory bench top 11. A template may be used to represent the operational area and to assist in defining the exact location of each workstation. Located on the bench top 11 are one or more work modules 13. A control station 14 is located adjacent to the laboratory bench 11. 10 The control station 14 may include a typical PC type computer 15, such as an IBM PC/2 or AT or any computer similar thereto, mounted on a desk 16 or other working surface. It would be clear to one of ordinary skill in the art, after perusal of the specification, drawings and 15 claims herein, that other types of computers may be utilized to control the movement of the robotic arm 10. A printer 17 is shown although other peripheral equipments may be utilized in conjunction with the computer 15.

Referring to the bench top 11, a plurality of 20 locating holes 12 are disposed at predetermined fixed locations relative to the robotic device 10. The locating holes are designed to receive modular workstations 13. Each modular workstation 13 is designed to be used in the performance of a particular process or step in one 25 laboratory task or test procedure. Thus each function required to be performed in a task is associated with a work module 13 which has a predisposed known position on the work bench 11.

There exist in the prior art a number of methods by 30 which the location of a particular work module 13 can be supplied to the computer 10. For example each work module 13 may include a floppy disk which would contain the physical characteristics of the work module, such as its height, width and length. The customized data for each 35 module would be fed into the central processing unit of the computer and would query the operator, for example through a CRT display, to provide the location of the work

module. The operator through the keyboard input would specify the location of the module on the locating grid. Thus for each work module or step of a task the computer would have stored in its memory the physical 5 characteristics and location of the module.

In a preferred embodiment, the robotic device 10 is capable travel in an "X" direction along a lead screw 20. Disposed at right angle to and vertical with respect to the lead screw 20 is a second lead screw 21 which is 10 capable of traversing lead screw 20. In addition, a gear or belt is capable of rotational movement relative to the lead screw 20. Coupled to the lead screw 21 is a lead screw 22 which is disposed at a right angle. A robotic hand 23 is mounted on lead screw 22 and is capable of 15 rotation. The sample to be assayed (which may be a tissue sample) is mounted on the hand 23.

Thus the hand 23 on which the sample is mounted is capable of "X" movement along lead screw 20, "Y" movement along lead screw 21, and "Z" movement along lead screw 22. 20 In addition, the lead screw 22 is rotatable and the hand 23 is rotatable. The system illustrated is capable of motion relative to five axes. Although the system is illustrated using lead screws 20, 21 and 22, it would be clear to one of ordinary skill in the art, after perusal 25 of the specification, drawings and claims herein, that other robotic equipment could be provided that could decrease or increase the number of axes, that other techniques other than lead screws, (such as gears or belts or other devices) could be used, and that such other 30 equipment or techniques would be workable, and are within the scope and spirit of the invention.

Typically, the range of movement along the "X" axis may be 72 inches, along the "Y" axis 12 inches, and along the "Z" axis 18 inches. Such a typical range of movement 35 could provide approximately eighteen cubic feet of operational area.

System Operation

In order to illustrate the operation of this invention, let it be assumed that the laboratory has five example tasks to accomplish. For purposes of 5 illustration, the five steps in each of the tasks will be utilized to demonstrate the multitasking capabilities of the invention. The five tasks and the five steps of each of the tasks are shown in Table 1 herein.

It is apparent from Table 1 that some of the tasks 10 utilize the same steps such as Pad 1 or Buffer 1. If these steps were to be carried out in accordance with the principles of this invention, it would be necessary to provide only fourteen work modules even though twenty five steps were being performed. Disposed on the grid would be 15 a separate work module for each of the fourteen different steps listed above. Thus there would be a Pad 1 module to be used in carrying out seven of the above steps. Alternatively, the user could provide multiple modules, each capable of performing the pad function. A Buffer 1 20 module would be used for five of the steps and a Buffer 2 module for two of the steps. Each of the remaining steps would have a module disposed on the grid to perform the necessary work associated with the step.

Table 1 -- FIVE TASKS

25	Task #1	Basic Fuchsin Staining
	Step #1	Buffer 1
	Step #2	Buffer 2
	Step #3	Basic Fuchsin
	Step #4	Pad 1
30	Step #5	Buffer 2
	Task #2	Azure II & Methylene Blue Counterstaining
	Step #1	Azure II
	Step #2	Pad 1
	Step #3	Buffer 1
35	Step #4	Pad 1
	Step #5	Methylene Blue

	Task #3	Tissue Fixation
	Step #1	Isotonic Rinse
	Step #2	Primary Fixative
	Step #3	Buffer 1
5	Step #4	Buffer 2
	Step #5	Secondary Fixative
	Task #4	Immunocytochemistry
	Step #1	Buffer 1
	Step #2	Pad 1
10	Step #3	Blocking Antibody
	Step #4	Pad 1
	Step #5	Buffer 1
	Task #5	Slide Silinizing
	Step #1	APTES
15	Step #2	Toluene
	Step #3	Water
	Step #4	Pad 1
	Step #5	Oven

It is often essential that the step of the task be  
20 performed within certain time limits. The timing of some  
steps can be critical. Figure 4 is a flowchart showing a  
time line for the five steps of the tasks in Table 1. It  
should be noted that Task- #1, Step #1 commences at 9:00  
and has a duration of approximately fifteen minutes,  
25 inclusive of the time necessary to transport the sample to  
the location where Step #2 is performed. Thus Step #2  
will commence at approximately 9:15. It should be noted  
that the timing for the start of Step #2 has some leeway  
in that it can commence between 9:15 and 9:18, providing  
30 leeway of three minutes. Step #2 has a duration of  
approximately eleven minutes and the sample is transported  
to the location where Step #3 will be performed. The time  
for performing Step #3 is critical as indicated by the  
lack of interval for the starting times. Step #3 must  
35 commence at 9:26. Fourteen minutes later the sample is  
undergoing Step #4, which can commence any time between  
9:40 and 9:50. The last Step #5 is performed at 9:51. It

should be noted that if each Step is commenced at the outer time limit Step #5 may not begin until 10:22.

In a similar manner it can be determined from figure 4 that the five steps of Task #2 may consume 1 hour and 34 minutes, Task #3, 1 hour and 9 minutes, Task #4, 1 hour and seventeen minutes and Task #5, 1 hour and sixteen minutes. Thus if the five steps of the tasks shown were to be performed sequentially the total time to completion would be six hours and thirty eight minutes.

10 Referring to figure 5, the multitasking method of this invention is therein illustrated to show the time interleaving of the steps of the multiple tasks. Assuming again for purposes of illustration and simplification of explanation that we are desirous of performing the same 15 five steps for the same five tasks. Under the control of the computer the robotic hand would be commanded to obtain sample #1 or alternatively the sample could be brought to the robotic hand and for grasping. The hand retaining the grasped sample would move the sample to the location of 20 the work module for Task #1, Step #1, i.e., Buffer 1. The sample would be freed from the hand and left at the work module. The hand would proceed to the location of sample #2 where it would grasp the sample and carry it to the work station where Task #2, Step #1 would be performed.

25 Each of the five samples would in turn be grasped by the robotic hand and transported to the work module associated with the first step of the task to be performed on each sample. It should be noted that the design of the Buffer and Pad work modules permit the simultaneous 30 treatment of at least two samples from different tasks. Alternatively, two work modules could be provided so that each sample could be treated in a different module.

After locating sample #5 in the Task #5, Step #1 module, the robotic hand returns to the module for Task 35 #5, Step #1 and grasps the sample #5 and transports it to the module for task #5, Step #2. Following the path illustrated in figure 5, the hand proceeds from the Task

#5, Step #2 module to Task #3, step #3 module where it grasps sample #3 and transports it to task #3, Step #2 module where the sample is deposited. The hand then returns to the location of the first sample which is in 5 the module associated with Task #1, Step #1 and takes it to the module for Task #1, Step #2. The hand return to the location sample #4 and carries it to Task #4, Step #2 and then at the appropriate time transports the same sample to Step #3 of Task #4.

10 At this point in the operation of the system, the computer detects that Task #1, Step #3 and Task #2, Step #2 are both scheduled to start at the same time, 9:26. In order to resolve the conflict the system utilizes a technique, herein termed "fuzzy timing", to process the 15 control of the robotic hand and optimize the process. Fuzzy timing may comprise the window of time during which each process (Task) step may occur without affecting the process results. Some steps of a process may be critically timed, i.e., the time required for that step is 20 exact, such as Task #1, Step #3 in figure 5, but in general most steps a process the timing is less critical and may comprise any amount of time within a known range and thus are noncritical in their timing, such as Task #2, Step #2, which has a window of 4 minutes, as shown in 25 figure 5. The system of this invention uses these windows of time to advantage as to optimize (minimize) the time necessary to complete the multiple tasks.

The use and advantages of "fuzzy timing" can be 30 illustrated by considering two different tasks, each having a process step terminating at the same time or within moments of the another. Assuming that both steps are critically timed in so far as the termination time is concerned, it is apparent that other samples from the two different steps can not be moved to the next step in each 35 process simultaneously since concurrent movement of two samples is not within the capabilities of this embodiment. Thus it is necessary to adjust the starting times for the

two steps relative to each other so that the ending times will allow for the movement of each sample to its next process step. While this can be done quite easily, it is clear that the mere adjustment of a starting time for a 5 step in the process may well cause other timing conflicts. It is possible that under such conditions the system could not support simultaneous throughput of multiple processes unless the timing was altered.

Fuzzy timing allows the system additional 10 flexibility since by providing a window of time at each noncritically timed process step, conflicts will be minimized through the adjustment of timing at the step level, rather than by shifting the timing of the whole process or task.

15 System Control By Operator

In order to use the system of this invention the operator (which might be a human user or a control processor) may first determine the processes that are to be carried out the apparatus. Each step of each process 20 may be defined. To assist the user an index of work stations may be provided to allow the user to determine which process steps can be employed. Alternatively, each work station can be represented by an icon on the CRT display and a help index made available that the user may 25 determine the capabilities of each workstation by referring to the icon and its associated help screen.

As previously described with reference to figures 1-2, the apparatus of the invention uses a locating grid or template presenting the operational work area reachable 30 by the robotic device 10 in which the work station locations may be defined. Each position on the grid is accurately determined and can be imparted to the computer to provide certainty of location. The exact relative position of each work station may be stored in the control 35 system. The use of the predetermined grid locations permits the user of this system to have the freedom of

designing individual templates to match the user's need and to design the steps of a process to provide relative limited ability in creating processes, limited only by the available work stations.

5       A graphic replica of the grid in which the work stations located is provided on the screen of the computer, such as shown in figures 6-8. Included in this graphic is the robotic arm position. In order to quickly input the steps of a process to the computer (1) a  
10 template builder and (2) a process builder have been created to interact with graphic replica of the work area. These two tools, template builder and process builder, allow the user to design a new process or modify an old process, easily and quickly without the need to have  
15 knowledge of computer programming. Through the use of a keyboard or mouse, the two builder tools are rendered interactive with the user.

A work station grid area may typically have holes disposed on one inch centers, or any other predetermined  
20 pattern. As is usual the columns of holes may be identified by letters while the rows of locating holes may be identified by numbers. Thus each hole can be uniquely identified by a letter-number combination.

Work station units or peripherals have been designed  
25 which have elements which cooperate with the grid locating holes and thus facilitate the exact location of each station. When located on the grid each work station will have a unique describer positively identifying its location.

30       Thus the user may commence operating the system by viewing a graphic representation of the work area surrounded by icons representing various work stations. As will be described below the user can quickly design a new template if so desired. Alternatively, the template  
35 may be called up from a disk by the computer.

The steps of the process are communicated to the computer through the use of an interactive peripheral such

as a mouse. The operator locates the mouse cursor on the icon representing the first step of the process and drags the icon to the desired location. Thus by pointing and clicking the mouse the work stations necessary to 5 accomplish the steps of the process are disposed on the graphic grid. It is of course desirable that the physical workstations be located on the grid in the locations shown on the display. Alternatively, the location of the work station can be fed into the computer in other ways, such 10 as through the keyboard or even by locating the physical work station on the grid with feedback to the computer identifying the work station and location.

Thus an unsophisticated user has the ability to design processes quickly imparting great flexibility to 15 this apparatus. It should of course be recognized that this information can be stored on a disk and the apparatus set up accomplished by reading the information off a disk into the memory of the computer.

In creating the template the operator uses a mouse 20 to draw replicas of each station on the screen, such as shown in figure 7, a template building screen. Each station is given a unique identification which may be a name, symbol or code. The dimensions of the station may be drawn on the screen and in particular it is essential 25 that the height of the work station is recorded. The position, identification, height and other dimensional criteria are stored in the RAM memory of the computer CPU. When the template is completed it may be stored to disk as a template file, to be recalled as needed.

30 As is not unusual in the operation of computers, provisions are made to add, delete, move, resize or duplicate any of the stations. Any available template previously stored may be recalled to be used or to assist in the creation of new templates. Of course the apparatus 35 may have the ability to enable the operator to print out a graphic replica of the screen and a list of station positions, identifications, heights or other dimensions.

Once the template is complete the operator may use the stations of the template to create a process, step by step.

The process builder, like the template builder, uses 5 a graphic replica of the workstation area on the computer screen, such as shown in figure 8, a process building screen. One of the templates previously created by the template tool builder described above, is recalled from memory and displayed on the screen together with the work 10 area. The screen cursor is moved to the desired station icon and the particular station is selected. This procedure may utilize a mouse and a point and click procedure.

Each station of the process is selected in sequence 15 and the station is then added to a list denoting the steps of the process in sequential order. The robotic device would ultimately be controlled to move to each of these stations in the order in which they were added the process list. Since the characteristics of each work station were 20 previously stored in the computer, the robotic device would be programmed for the proper movement. For example, the height of each station was previously stored in the memory, and if the robotic arm were to traverse the area in which a high work station was located, it would be 25 instructed to elevate the hand so that any sample mounted thereon would clear the high work station. It is also possible to design the operational area to have clear paths or lanes defining travel routes for the robotic device 10. In any event, the movement of the robotic 30 device among the workstations may be designed to be free of collisions based upon recognition of the entity, position and geometry of the workstations. As will appreciated as the number of work stations increase the amount of information that should be considered in order 35 to avoid collisions and otherwise avoid conflicts in instructions also increases.

Following the graphic design of the steps of the process, the process list would be called up on the screen and the procedure for each step would be imparted, such as shown in figure 9. This procedure would essentially 5 indicate a range of time each sample should remain at each station. For each step a minimum time and a maximum time for the sample to remain at the work station would be recorded. As noted herein, the minimum time may be specified to be zero, and the maximum time may be 10 specified to be infinity. The times for each station, except where the timing is critical, would allow the system a timing window which can be used to avoid timing conflicts between different steps of separate tasks and thus maximize the multitasking capabilities of the 15 apparatus.

Pseudocode for Designing or Running New Processes

The method carried out by the control station 14 for template building and process building may be described by pseudocode shown in Tables 2-3 herein, respectively. It 20 would be clear to one of ordinary skill in the art, after perusal of the specification, drawings and claims herein, that modification of known processor systems to perform the functions disclosed in this pseudocode (as well as in other pseudocode disclosed herein) would be a straight 25 forward task and would not require undue experimentation.

Table 2 -- TEMPLATE BUILDER

```
procedure template_tool();
  set up screen;
  draw robot replica graphic;
  5  draw grid;
  display mouse cursor;
  select template design tool;
  while (not finished)
    select tool;
  10  case (edit tool)
      add:           draw new station on screen via
                     mouse by dragging mouse away
                     from start point while having
                     mouse button 1 depressed; update
                     screen with a rectangle being
                     displayed along cursor
                     displacement;
      15           enter id via keyboard;
                     position height of station;
                     store position and id;
      20           select:           move cursor to station via
                     mouse;
                     click mouse to select;
                     selected station changes color
                     to show it is selected;
      25           delete:          click mouse button 1 to delete;
                     move:              place move crosshair on selected
                     station;
                     place cursor on crosshair;
                     30           press mouse button 1 down and
                     drag station to new position;
                     screen update after each new
                     grid position move;
```

```
      resize:      place  resize  crosshair  on
                     selected station;
                     place cursor on crosshair;
                     press mouse button 1 down and
                     drag station to new size;
                     screen update after each new
                     size;
      5          duplicate:   get current selected station
                     position, size and height
                     information;
                     offset duplicate to new
                     position;
                     add id;
                     store new station position and
                     id;
      10         case (edit tool) end;
      15         case (file tool)
                     get template:   display list of template files;
                     select via mouse cursor;
                     open selected template;
                     display template stations on
                     screen;
                     hold station records in RAM;
      20
      25         save template:  display list of template files;
                     select via cursor or enter new
                     name via keyboard;
                     store template file to disk;
                     case (file tool) end;
end (template_tool);
```

Table 3 -- PROCESS BUILDER

```
procedure process_tool();
  set up screen;
  draw robot replica graphic;
5   draw grid;
  draw process list;
  display mouse cursor;
  case (file tool)
    get template:      display list of template files;
10
    select via mouse cursor;
    open selected template;
    display template stations on
    screen;
    hold station record in RAM;
15   get process:      display list of process files;
    select via mouse cursor;
    open selected process;
    display process list in list
    window;
20
    display associate template
    stations on the screen;
    hold process station records in
    RAM;
    save process:      display list of process files;
25
    select via cursor or enter new
    name via keyboard;
    store process file to disk;
    case (file tool) end;
    case (select_tool):
30
      if cursor in work station and on a station and mouse
      button 1 down then add station to process list;
      if cursor in process list and on list member and
      mouse button 1 down then delete from list;
      case (select_tool) end;
35   case (window select)
```

After the station sequence has been entered and the times for each step recorded, the process may be stored to disk as a process file. The process file may be loaded in 15 the future and the apparatus used to run the same process at a later date. Of course the template file may be linked to the process file so that when a process is called up from storage and run on the computer the template files used in the process may be automatically 20 called up and displayed on the computer screen.

The procedure list on which the times at each step were recorded may be called up at any time and for the stations still not used by the robotic device, adjustments to the timing could be made provided that the steps in the process which are to have their timing altered have not been reached. Thus the operator can adjust the timing of the step seven as the process is running.

## Visual Operator Interface

Figure 6 shows a multitask monitoring screen 61 as viewed by an operator. A multitask monitoring screen 61 may be shown on a display device coupled to the computer 15, such as a display monitor. The multitask monitoring screen 61 may comprise a display section 62, a menu section 63, and a status section 64.

35 The display section 62 may show a representation of  
the robotic device 10, bench top 11, holes 12, work

modules 13, and related equipment. For example, the display section 62 may show positions for workstations 13 for a selected process.

The menu section 63 may show command options and 5 suboptions which are available to the operator and may allow the operator to select one or more command options and suboptions. For example, the menu section 63 may have a menu with the command options "GET PROCESS", "BUILD PROCESS", "PROCESS LIST", "GET TEMPLATE" AND "BUILD 10 TEMPLATE". The operator may display available command options and select one or more command options in the menu section 63, by means of a pointing device, such as a mouse, as is well known in the art.

The status section 64 may show a set of status 15 information about processes. For example, the status section 64 may show five processes which are in progress, and may show for each process the current step it is on, the total time it has taken (both for the current step and for the entire process), and the time remaining that it 20 will take (both for the current step and for the entire process). Note that elapsed time for the current step may be zero because the robotic device 11 might wait for the proper time before depositing the sample in the workstation 13 for that process step, e.g., holding the 25 sample in the robotic hand 23 if travel from a prior step took less time than expected. The status section 64 may also show the X, Y and Z position of the robotic arm.

Figure 7 shows a template building screen 71 as viewed by an operator. A template building screen 71 may 30 be shown on a display device coupled to the computer 15, such as a display monitor, in like manner as the multitask monitoring screen 61. The template building screen 71 may comprise a display section 62, a menu section 63, and a status section 64, in like manner as the multitask 35 monitoring screen 61.

When using the template building tool, described herein, the operator may view the template building screen

71 and manipulate the commands and elements thereon by means of a pointing device, such as a mouse. A detailed description of how the operator may use the template builder tool is given herein.

5 Figure 8 shows a process building screen 81 as viewed by an operator. A process building screen 81 may be shown on a display device coupled to the computer 15, such as a display monitor, in like manner as the multitask monitoring screen 61. The process building screen 71 may 10 comprise a display section 62, a menu section 63, and a status section 64, in like manner as the multitask monitoring screen 61, and a workstation section 85.

15 The workstation section 85 may show a set of names or other identifiers of workstations 13. The operator may 15 select one or more workstations 13 for inclusion in a process, by means of a pointing device, such as a mouse.

20 When using the process building tool, described herein, the operator may view the process building screen 81 and manipulate the commands and elements thereon by 20 means of a pointing device, such as a mouse. A detailed description of how the operator may use the process builder tool is given herein.

25 Figure 9 shows a process timing screen 91 as viewed by an operator. A process timing screen 91 may be shown 25 on a display device coupled to the computer 15, such as a display monitor, in like manner as the multitask monitoring screen 61. The process timing screen 91 may comprise a plurality of lines 92, each of which may have an identifier section 93, a name/descriptor section 94, a 30 minimum time section 95 and a maximum time section 96.

35 When using the process building tool, described herein, the operator may view the process timing screen 91 and enter minimum times (in the minimum time section 95) and maximum times (in the maximum time section 96) for 35 each process step at each line 92. Each process step may thus have a line 92 with an identifier in the identifier

section 93 and a name or descriptor in the name/descriptor section 94.

The minimum time section 95 for a line 92 may specify a minimum time which the designated process step 5 may take, which might be zero. If the minimum time is zero, additional data may be noted to indicate whether the designated process step may take a single tick of a timing clock for the robotic device 10, or if the designated process step may be skipped entirely.

10 The maximum time section 96 for a line 92 may specify a maximum time which the designated process step may take, which might be infinity. If the maximum time is infinity, the system may delay completion of the designated process step until after all other process 15 steps with finite maximum time have been completed.

Each line 92 may also have an additional data section 97 for the designated process step, which may specify whether (1) the step is to be done, (2) the step is to be skipped, or (3) the process is to be "held" or 20 temporarily halted at the designated process step for input from the operator. In the latter case, for example, the process might be "held" at the designated process step until an operator confirms that the process should continue.

25 Multitasking and Optimization

Having delineated all the steps of all the procedures, the computer may determine the most efficient manner for carrying out the procedure. The task would be simple if the steps of the first process were to be 30 completed before the apparatus started on the second process. Through the use of time interleaving, multiplexing or multitasking the computer is utilized to keep track of multiple operations so as to perform a number of different processes each having a multiplicity 35 of steps simultaneously.

In multitasking, a number of samples, each undergoing separate exposures may all be worked on simultaneously. In time interleaving, the robotic arm may operate through a sequence which is determined by the 5 timing of the individual steps of many processes and the robotic arm transports different samples in a time efficient sequence rather than a process ordered sequence. Although the robotic device can only move one sample to a work station at a time, the entire system is continuously 10 monitoring, scheduling and processing all tasks and their times at each station concurrently. At each step the process performed at that workstation continues (e. g., chemical reactions) even when the robotic arm is not currently attending to it. In other words, the sample is 15 disposed in the workstation and the robotic arm continues to grasp another sample. The process step continues to work on the first sample while the robotic arm is attending or transporting the second sample. The multiple process steps that are being done, one to each sample, are 20 being done in parallel and are not serial processes.

In fact the robotic arm works on a sample for a short period of time during which it usually transports a sample to a work station and then leaves that sample and works on another sample or samples before returning again 25 to the first sample. Thus the robotic device work on each sample is suspended during the time interval that it is working on another sample or during which the samples are being processed at a work station.

The multitasking of the different processes is 30 dependent upon the instructions issued to the robotic device, relative to the timing of each of the steps in the multiple processes and the optimization of the multitasking operations, to move the samples at the scheduled times determined by the computer inputs.

35 The computer control (software) may first determine all the robotic movements necessary to complete the entire run of all the steps in all the processes to be run. This

determination may be completed before any movement is initiated. If at any time during the running of the multitasking any steps are added to one or more of the processes or any of the steps are reconfigured during the 5 run, a new determination may be completed wherein the computer recalculates all the movements necessary to complete the run and insures that there is no time interference created by the modification to the run. This method of predetermining the movements can of course be 10 replaced by a real time method of determining movement but it is believed that the predetermining method is more advantageous. The predetermining method identifies time conflicts, if any, where the robotic device would be required to perform two tasks simultaneously, resolves any 15 such conflicts that may exist, and optimizes the schedule for the minimum time required to complete the entire run of the multiple processes.

This method of predetermination employs certain decision making procedures which are designed to permit 20 the computer to resolve time conflicts and iteratively optimize the schedule. An iterative optimization method is used because the complexity of scheduling different multiple tasks, each with the possibility of having multiple critically timed steps, is too complex to be 25 solved by using mathematical techniques. In addition, the decision making rules allow the resolution of other conflicting requirements for other resources such as the peripheral equipment or work station modules, which may be used in conjunction with the robotic equipment.

30 As described above, a predetermined schedule may be developed to resolve time and resource conflicts and the schedule may be iteratively optimized to minimize the time required to complete the steps of the multiple processes. In order to interleave the steps of the multiple processes 35 each step of each task is examined at predetermined intervals, e.g., one minute. A calculation is made of the time to completion of the current step. If the step

incubation time is finished a move condition results. If that is the only move condition during this time, i.e., only one move condition occurs, the robotic device will be scheduled to move to the next step in accordance with the 5 predetermined schedule. However, if more than one sample is scheduled to move time arbitration ensues. Time arbitration determines the fuzzy time window for each of the time conflicting steps and selects the sample in the most time critical step to move. If more than one step 10 has a critical time, the computer compares the times during the previous movement and varies the timing of the previous tasks to resolve or prevent bottlenecks from occurring. In a similar manner a single resource can be scheduled to work on two different samples during the same 15 time period and such conflicts can be resolved in a similar manner using the arbitration method.

Pseudocode for Multitasking

The method carried out by the control station 14 for multitasking may be described by pseudocode shown in 20 Tables 4-8 herein. It would be clear to one of ordinary skill in the art, after perusal of the specification, drawings and claims herein, that modification of known processor systems to perform the functions disclosed in this pseudocode (as well as in other pseudocode disclosed 25 herein) would be a straightforward task and would not require undue experimentation.

Table 4 -- MULTITASKING DATA STRUCTURE

STRUCTURE TASK ARRAY [ 11500 elements ]

	BYTE	PROCESS NUMBER;
30	BYTE	TASK NUMBER;
	CHAR [ 25 ]	TASK NUMBER;
	INTEGER	TASK X COORDINATE OF WORKSTATION;
	INTEGER	TASK Y COORDINATE OF WORKSTATION;
	LONG INTEGER	ENCODED REAL TIME FOR PICKUP OR
35		DROPOFF;

CHAR [1] DROPOFF/PICKUP FLAG;  
CHAR [5] MOVE\_FLAG;  
5 { When TRUE the process flagged needs to move  
to next task in progress. This information is  
entered into the task array. If multiple flags  
are set simultaneously the process steps must  
be arbitrated.}  
CHAR [5] RESOURCE\_FLAG;  
10 { If set TRUE, two or more tasks require the  
same resource. Resource arbitration is done to  
resolve all conflicts. }

## Table 5 -- MULTITASKING (BUILD SCHEDULE)

PROCEDURE BUILD\_MULTITASK\_SCHEDULE ()

15 { This routine is called a number of times with  
different seeding to build a statistical sampling of  
a number of schedules. The calling routine picks  
the most optimul schedule to run. }

BEGIN  
20 { Initialize timer and pick a process for first  
move. For iterative tasks, processes will be  
started in various orders to seek task builder and  
establish different scheduling. At each timer tick  
all processes are examined to check whether it is  
time to move to next position. If TRUE the task  
25 will be entered into the task array at the scheduled  
time. If more than one process needs movement at  
the same timer tick, time arbitration ensues. If  
two or more processes need the same resource,  
resource arbitration is undergone. This process  
30 continues until all tasks in all processes are  
complete. }  
TIME = 0;  
START\_FIRST\_PROCESS;  
WHILE NOT ALL PROCESSES STARTED DO BEGIN  
35 INCREMENT TIMER BY 1;  
IF ANY TASK NEEDS MOVEMENT THEN

```

        SET TASK MOVE FLAG
        ELSE
            START_NEXT_PROCESS;
        IF MOVE_FLAG > 1 THEN TIME_ARBITRATE ();
5           { check for multiple moves}
        IF TASK_MOVE THEN ADD TASK TO TASK_ARRAY [TASK_
        COUNTER]
        END;
        WHILE NOT ALL PROCESSES COMPLETED DO BEGIN
10       INCREMENT TIMER BY 1;
        IF ANY PROCESS NEEDS MOVEMENT THEN SET TASK
        MOVE FLAG;
        IF MOVE_FLAG > 1 THEN TIME_ARBITRATE ();
           { check for multiple moves }
15       IF TASK_MOVE THEN ADD TASK_ARRAY [TASK];
           { check for resource use }
        END;
        END;

```

Table 6 -- MULTITASKING (TIME ARBITRATE)

```

20  PROCEDURE TIME_ARBITRATE ()
        { If two or more processes must be moved
        simultaneously, the times are arbitrated, first by
        examining fuzzy time range and adjusting those
        process tasks with fuzzy time. If the colliding
25  processes are critically timed the processes' prior
        tasks are arranged to circumvent the collision.
        This procedure is called in REARRANGE_ARRAY (). }
        INTEGER FUZZY_TIME_COMP      = MAX_TIME;
        { set the comparator to a maximum value }
30        BYTE   CRITICAL_FLAG      = 0;
        BYTE   CRITICAL_FLAG_ARRAY [5] = { 0, 0, 0, 0, 0, 0 };
        BEGIN
            FOR I = 1 TO MAX PROCESSES
                IF (PROCESS [I].MOVE_FLAG_SET AND
35                FUZZY_TIME [I] < FUZZY_TIME_COMP)
                THEN BEGIN

```

34

```
      TASK_MOVE = I;
      { finds shortest fuzzy time }
      FUZZY_TIME_COMP = FUZZY_TIME [I]
      IF (FUZZY_TIME = 0) THEN BEGIN
          SET CRITICAL_FLAG;
          SET CRITICAL_ARRAY [TASK];
          END;
      END;

      { If two or more processes need to move
      immediately a rearrangement of earlier
      interleaved tasks occurs to settle
      conflicts at this point if a fuzzy time
      range settle the conflict the process with
      the shortest fuzzy time value is set to
      move. }

      IF CRITICAL_FLAG > 1 THEN REARRANGE_ARRAY ();
      ELSE
          ADD TASK_ARRAY [TASK_MOVE];
      END;

20  Table 7 -- Multitasking (Resource Arbitrate)
      PROCEDURE RESOURCE_ARBITRATE()
      { If two or more processes need the same resource
      (physical location), fuzzy times for the processes
      in question are examined to evaluate whether the
      time slack can settle the conflict. If not, the
      processes prior tasks are rearranged to circumvent
      the collision.}
      BYTE      CRITICAL_FLAG          = 0;
      {initialize critical flag}
      25        BYTE      CRITICAL_FLAG_ARRAY [5] =
                  {0, 0, 0, 0, 0, 0,};

      BEGIN
      {Compare process task fuzzy time with other process
      actual task time.}
      30        COMPARE  CRITICAL_PROCESS_1_FUZZY_TIME  WITH
                  CRITICAL_PROCESS_2_TASK_TIME;
```

35

```
IF > TASK_MOVE = PROCESS_2;  
ELSE  
COMPARE CRITICAL_PROCESS_2_FUZZY_TIME WITH  
CRITICAL_PROCESS_1_TASK_TIME;  
5 IF > TASK_MOVE = PROCESS_1;  
IF TASK_MOVE TRUE  
ADD TASK_ARRAY [TASK_MOVE];  
ELSE BEGIN  
SET CRITICAL_FLAG;  
10 SET CRITICAL_FLAG_ARRAY [TASK];  
REARRANGE_TASK_ARRAY ();  
END;  
END;
```

Table 8 -- Multitasking (Rearrange Tasks)

```
15 PROCEDURE REARRANGE_TASK_ARRAY ()  
{To prevent conflicts which cannot be arbitrated  
with fuzzy timing the processes in conflict are  
examined at their previous step(s) and timing  
adjusted in that task to remedy the conflict at the  
20 current task. After time adjustment of the critical  
process the task array is reset to the newly  
adjusted position and returns to the multitask  
builder and reworks the rest of the tasks in all  
processes.}  
25 BEGIN  
(Find the last time the critical process was moved.)  
REPEAT  
POSITION = POSITION - 1;  
UNTIL TASK_ARRAY [POSITION] =  
30 CRITICAL_FLAG_ARRAY [TASK];  
(Adjust timer.)  
INCREMENT TASK [TASK_ARRAY  
[POSITION].MIN_TIME] BY X;  
(Reset position and time.)  
35 SET POSITION TO CURRENT TASK_ARRAY VALUE;  
SET TIMER TO CURRENT TASK_ARRAY VALUE;
```

RETURN TO MULTITASK\_BUILDER;  
END;

It would be clear to one of ordinary skill in the art, after perusal of the specification, drawings and 5 claims herein, that there is a multitude of interleave paths that can be taken to achieve multitasking of a plurality of processes. Each path will in all probability have a different time to complete all of the steps of all of the processes. In view of this it will be appreciated 10 that for optimum efficiency it is necessary to select the optimum path which will take the minimum time to complete. As a practical matter an iterative process can be used in which the interleave path is computed several times. Each time the interleave variables are iterated they are 15 ordered and computed differently so that different results are obtained for each iteration. The number of iterations necessary to arrive at an optimized path can be computed statistically by taking the number of steps in each task and the number of tasks to be performed. Since run time 20 of the paths calculated from the numerous iterations follow a normal distribution curve, the minimum number of iterations necessary to achieve a path that will be among the faster run times can be calculated.

Alternative Embodiments

25 While preferred embodiments are disclosed herein, many variations are possible which remain within the concept and scope of the invention, and these variations would become clear to one of ordinary skill in the art after perusal of the specification, drawings and claims 30 herein.

**Claims**

1. A robotic system to transport a plurality of samples, each sample undergoing a test procedure having a plurality of steps, to a plurality of work stations each associated with one of said steps wherein said samples are undergoing said test procedures substantially simultaneously comprising:
  - a. a multi axis robotic device means having a predetermined working range area,
  - 10 b. a work table coextensive with said working range area,
  - c. a plurality of work modules each associated with one of said steps disposed at identifiable locations on said work table,
  - 15 d. computer means to control said robotic device,
  - e. means to input to said computer the physical dimensions and location on said work table of said work modules,
  - 20 f. means to input to said computer the sequence of steps associated with each of said tests, each of said steps having a time of performance during which said sample must be located at the step's associated work station, said performance being completed at a step end time,
  - 25 g. means associated with said robotic means to couple to a sample and capable of holding said sample during transportation between steps,
  - h. means to schedule said robotic device to move a sample sequentially to the work stations associated with the test said sample is undergoing and deposit said sample at said work station until said step end time is reached,
  - 30 i. means to schedule the movement of each sample after the first step in the test so that it occurs while the other samples are disposed in their work stations;

j. means to cause said robotic device to transport said samples responsive to said end times.

2. A robotic system in accordance with Claim 1 which further includes means to compare the scheduled time 5 of movement of each of said samples to determine if conflicts exist, means to determine if multiple samples are scheduled to be disposed at the same work station during the same time, and means to adjust the time schedule of any sample within a predetermined time ranges 10 to resolve and conflicts discover by said comparison means.

3. A robotic system according to claim 1 which further includes means to optimize the scheduling of said device, said means to optimize including iteration means 15 to produce multiple different schedules, means to provide statistical information concerning the time distribution such iteration should result in and means to halt said iteration and accept one of the schedules that comes close to the optimum schedule based on said statistical 20 distribution.

4. Computer means to control the scheduling of multiple tests, each comprising several distinct steps, each step having a starting time and a completion time associated therewith comprising:

25 a. means for determining a starting time and a completion time for each of the steps in the multiple tests,

b. means for scheduling the steps of said multiple tests in a single time sequence arrangement 30 interleaving the steps of said tests,

c. means for detecting time conflicts of interfering starting and completion times of said interleaved steps,

d. means for resolving said time conflicts by adjusting the starting and completion times of one or more of said steps.

5. A method for controlling a robotic system for simultaneously process a number of samples through a variety of different assays, each assay associated with one of said samples and having one or more steps processing said associated sample at a work station, each of said steps having a processing time during which the 10 sample must be located at said station wherein said robotic system includes:

a. a work table defining a work area;  
b. a plurality of work modules each designed to process a sample through one step of an assay and each 15 of said modules having physical characteristics associated therewith;

c. means to dispose each of said work modules within said work area;

d. means to determine the specific location 20 of each of said modules;

e. a robotic device having a plurality of movement axis and means to grasp one of said samples;

f. computer means having a central processing unit;

25 g. means to control said robotic device to cause said device to grasp and transport said samples responsive to the output of said central processing unit said method comprising the steps of

30 1. assigning a time to start each of said assays,

2. determining the desired start and completion times of each of said steps responsive to the start time for each of said assays and the processing time associated with each of the steps of said assays,

35 3. creating a schedule time interleaving of all of said steps responsive to said start times,

4. determining the existence of interfering times therein the start or completion time of one step is scheduled at the same time as the start or completion time of another step,

5 5. resolving, said conflicts to produce a nonconflicting schedule to perform all the steps of each of the assays in a time multiplexed manner,

6. reviewing and iterating the steps of this method to produce a practical optimized  
10 10 non-conflicting schedule,

7. providing data input to said central processing unit defining the location and physical characteristics of each of said work stations,

8. creating output signals from said  
15 central processing unit to control said robotic device in accordance said optimized schedule and input data to cause the robotic device to transport and deposit each of said samples in a work station in accordance with said schedule.

20 6. The method of simultaneously exposing a plurality of test samples to a multiplicity of tests, each sample being subjected to one of said tests and each test having a number of steps comprising

25 a. selecting the test to which each sample is to be exposed;

b. determining the steps that compose the selected tests;

c. ascertaining a time range for each step;

d. scheduling all of said steps into a single

30 program;

e. determining if time conflicts exist between steps of multiple processes;

f. adjusting the timing of any conflicting steps by altering the time ranges at each step to alter  
35 start or stop times;

to provide a time sequential arrangement for all the steps comprising all the tests.

7. A system for performing a plurality of independent analysis procedures simultaneously, each said 5 procedure having a sample and at least one process step for operating on that sample, said system comprising

a robotic arm for moving the samples among a plurality of processing stations; and

10 a processor for selecting, at a plurality of times, a sample to be moved, and for directing said robotic arm to move said sample to be moved; said processor having means for directing said robotic arm to interleave the process steps of said plurality of independent analysis procedures.

15 8. A system as in claim 7, wherein said processing stations are disposed in a set of grid locations, and wherein said robotic device comprises a bench robot with a rotatable tower and with sufficient degrees of freedom that it is able to reach each of the grid locations with 20 suitable movement.

9. A system as in claim 7, wherein said processing stations comprise workstations for performing individual steps of the analysis procedures.

10. A system as in claim 7, wherein at least one 25 said processing station comprises one of the group: a bioassay workstation, a biomedical workstation, a chemical process workstation.

11. A system as in claim 7, wherein said processor comprises a memory for storing a start time and an end 30 time for each said process step.

12. A system as in claim 7, wherein said processor comprises a memory for storing timing information for each said process step, said timing information comprising a range of times at which said process step may be in a 5 predetermined state.

13. A system as in claim 7, wherein said processor comprises means for selecting said sample to be moved in response to timing information about said procedures.

14. A system as in claim 7, wherein said processor 10 comprises

a memory for storing timing information for each said process step, said timing information comprising a range of times at which said process step may be in a predetermined state; and

15 means for determining an exact time to start each said process step in a first said procedure in response to timing information for at least one process step in a second said procedure.

16. A system as in claim 14, wherein said means for 20 determining comprises

means for generating a possible sequence of process steps;

means for examining said possible sequence for possible conflicts; and

25 means for altering said possible sequence in response to said timing information and said possible conflicts.

17. A system as in claim 14, wherein said means for determining comprises means for generating a possible 30 sequence of process steps;

means for examining said possible sequence for timing conflicts occurring before a known time value;

means for advancing said known time value from a beginning of said possible sequence to an end of said possible sequence;

means, when a first process step is found to 5 have a timing conflict with a second process step and said first process step has a range of times at which it may be started, for selecting an exact time to start said first process step; and

means, when a first process step is found to 10 have a timing conflict with a second process step and said first and second process steps have exact times at which they may be started, for backtracking said known time value and altering said possible sequence starting from said backtracked known time value to avoid said timing 15 conflict.

17. A system as in claim 14, wherein said processor comprises

means for generating a plurality of possible sequences of process steps;

20 means for evaluating each said possible sequence for total expected time; and

means for selecting one said possible sequence with a desired total expected time, so as to minimize a total time required to complete said procedures.

25 18. A system as in claim 7, wherein said processor comprises

a display screen;

means for identifying a symbol shown on said display screen in response to a selection from an 30 operator;

means for associating a process step with said symbol; and

means for recording an ordered sequence of said process steps.

19. A system as in claim 18, wherein said means for identifying comprises a pointing device.

20. A system as in claim 18, comprising means for receiving information from said operator about the process 5 step associated with said symbol.

21. A system as in claim 20, wherein said information comprises timing information.

22. A system as in claim 20, wherein said information comprises a minimum time and a maximum time 10 for said process step associated with said symbol.

23. A system as in claim 7, comprising  
a display screen;  
means for drawing a new symbol on said display  
screen in response to information from an operator; and  
15 means for associating a processing station with said  
new symbol.

24. A system as in claim 23, wherein said means for drawing comprises a pointing device.

25. A system as in claim 23, comprising means for 20 receiving information from said operator about the processing station associated with said new symbol.

26. A system as in claim 7, comprising  
means for monitoring progress information for said  
procedures; and  
25 means for altering a sequence of said process steps  
in response to said progress information and in response  
to information from an operator.

27. A system as in claim 26, wherein said means for altering comprises

means for receiving a command from said operator for changing said sequence of process steps; and

means for determining a new sequence of process steps in response to said command and in response to  
5 timing information about said process steps.

28. A system as in claim 26, wherein said means for altering comprises

means for generating a possible new sequence of process steps from a time said altering occurs onward;

10 means for examining said possible new sequence for possible conflicts; and

means for altering said possible new sequence in response to said timing information and said possible conflicts.

15 29. A system as in claim 26, wherein said means for determining comprises

means for generating a possible new sequence of process steps from a time said altering occurs onward;

20 means for examining said possible new sequence for timing conflicts occurring before a known time value;

means for advancing said known time value from the time said altering occurs an end of said possible new sequence;

25 means, when a first process step is found to have a timing conflict with a second process step and said first process step has a range of times at which it may be started, for selecting an exact time to start said first process step;

30 means, when a first process step is found to have a timing conflict with a second process step and said first and second process steps have exact times at which they may be started, for backtracking said known time value and altering said possible new sequence starting from said backtracked known time value to avoid said timing  
35 conflict; and

means for signalling an error when said known time value is backtracked beyond the time said altering occurs.

30. A method for performing a plurality of 5 independent analysis procedures simultaneously, each said procedure having a sample and at least one process step for operating on that sample, said method comprising the steps of

selecting, at a plurality of times, a sample to be 10 moved;

directing a robotic arm to move said sample to be moved by interleaving the process steps of said plurality of independent analysis procedures.

31. A method as in claim 30, comprising the step of 15 storing a start time and an end time for each said process step.

32. A method as in claim 30, comprising the step of storing timing information for each said process step, said timing information comprising a range of times at 20 which said process step may be in a predetermined state.

33. A method as in claim 30, comprising the step of selecting said sample to be moved in response to timing information about said procedures.

34. A method as in claim 30, comprising the steps 25 of

storing timing information for each said process step, said timing information comprising a range of times at which said process step may be in a predetermined state; and

30 determining an exact time to start each said process step in a first said procedure in response to timing

information for at least one process step in a second said procedure.

35. A method as in claim 34, wherein said step of determining comprises the steps of  
5 generating a possible sequence of process steps;  
examining said possible sequence for possible conflicts; and  
altering said possible sequence in response to said timing information and said possible conflicts.

10 36. A method as in claim 34, wherein said step of determining comprises the steps of  
generating a possible sequence of process steps;  
examining said possible sequence for timing conflicts occurring before a known time value;  
15 advancing said known time value from a beginning of said possible sequence to an end of said possible sequence;  
selecting an exact time to start said first process step when a first process step is found to have a timing  
20 conflict with a second process step and said first process step has a range of times at which it may be started;  
and  
backtracking said known time value and altering said possible sequence starting from said backtracked known  
25 time value to avoid said timing conflict when a first process step is found to have a timing conflict with a second process step and said first and second process steps have exact times at which they may be started.

37. A method as in claim 34, comprising the steps  
30 of  
generating a plurality of possible sequences of process steps;  
evaluating each said possible sequence for total expected time; and

selecting one said possible sequence with a desired total expected time, so as to minimize a total time required to complete said procedures.

38. A method as in claim 30, comprising the steps  
5 of

identifying a symbol shown on a display screen in response to a selection from an operator;  
associating a process step with said symbol; and  
recording an ordered sequence of said process  
10 steps.

39. A method as in claim 38, comprising the step of receiving information from said operator about the process step associated with said symbol.

15 40. A method as in claim 39, wherein said information comprises timing information.

41. A method as in claim 39, wherein said information comprises a minimum time and a maximum time for said process step associated with said symbol.

20 42. A method of operating a processor having a display screen for specifying a test procedure in a system for performing a plurality of test procedures, said method comprising the steps of

selecting a first location on said screen within a  
25 template displayed on a screen;

moving a copy of said template to a second location on said screen;

identifying a process step with said template and said second location; and

30 repeatedly performing said steps until an ordered sequence of said process steps has been determined.

43. A method of operating a processor having a display screen for specifying a test procedure in a system for performing a plurality of simultaneous test procedures, said method comprising the steps of

5 displaying a plurality of templates on said screen for viewing by an operator;

receiving a first signal from said operator indicative of a first location on said screen;

10 identifying said location with a first one of said templates;

receiving a second signal from said operator indicative of a second location on said screen;

displaying said first one of said templates at said second location;

15 identifying a process step with said template and said second location; and

repeatedly performing said steps until an ordered sequence of said process steps has been determined.

44. A method as in claim 43, comprising the step of  
20 receiving a third signal from said operator indicative of information about said process step.

45. A method as in claim 30, comprising

drawing a new symbol on a display screen in response to information from an operator; and

25 associating a processing station with said new symbol.

46. A method as in claim 45, comprising the step of receiving information from said operator about the processing station associated with said new symbol.

30 47. A method as in claim 30, comprising the steps of  
monitoring progress information for said procedures;  
and

altering a sequence of said process steps in response to said progress information and in response to information from an operator.

48. A method as in claim 47, wherein said step of  
5 altering comprises the steps of  
receiving a command from said operator for changing  
said sequence of process steps; and  
determining a new sequence of process steps in  
response to said command and in response to timing  
10 information about said process steps.

49. A method as in claim 47, wherein said step of  
altering comprises the steps of  
generating a possible new sequence of process steps  
from a time said altering occurs onward;  
15 examining said possible new sequence for possible  
conflicts; and  
altering said possible new sequence in response to  
said timing information and said possible conflicts.

50. A method as in claim 47, wherein said step of  
20 determining comprises the steps of  
generating a possible new sequence of process steps  
from a time said altering occurs onward;  
examining said possible new sequence for timing  
conflicts occurring before a known time value;  
25 advancing said known time value from the time said  
altering occurs an end of said possible new sequence;  
selecting an exact time to start said first process  
step when a first process step is found to have a timing  
conflict with a second process step and said first process  
30 step has a range of times at which it may be started;  
backtracking said known time value and altering said  
possible new sequence starting from said backtracked known  
time value to avoid said timing conflict when a first  
process step is found to have a timing conflict with a

second process step and said first and second process steps have exact times at which they may be started; and signalling an error when said known time value is backtracked beyond the time said altering occurs.

5 51. In a system for performing a plurality of independent analysis procedures simultaneously, each said procedure having a sample and at least one process step for operating on that sample, a data structure comprising an entry for each one of a plurality of process steps, 10 each said entry comprising a range of times at which said process step may be in a predetermined state.

52. In a system for performing a plurality of independent analysis procedures simultaneously, each said procedure having a sample and at least one process step 15 for operating on that sample, a data structure comprising a sequence of process steps indexed by a time value and indicating a start time and an end time for each said process step.

53. A data structure as in claim 52, comprising a 20 second sequence of process steps indexed by said time value, wherein said second sequence comprises process steps from a single procedure.

54. In a system for performing a plurality of independent analysis procedures simultaneously, each said 25 procedure having a sample and at least one process step for operating on that sample, a data structure comprising an ordered sequence of entries, each said entry comprising a symbol on a display screen and a process step.

55. A data structure as in claim 54, wherein each 30 entry comprises timing information for said process step.

52  
AMENDED CLAIMS

[received by the International Bureau on 15 December 1992 (15.12.92);  
original claims 2-8, 14, 18, 23, 26, 30, 34 and 51 amended;  
new claims 56-61 added; other claims unchanged (19 pages)]

j. means for causing said robotic device to  
transport said samples responsive to said end times.

2. A robotic system to transport a plurality of samples, each sample undergoing a test procedure having a plurality of steps, to a plurality of work stations each associated with one of said steps wherein said samples are undergoing said test procedures substantially simultaneously, said system comprising
  - 5 a multi axis robotic device having a predetermined working range area;
  - 10 a work table substantially coextensive with said working range area;
  - 15 a plurality of work modules each associated with one of said steps disposed at identifiable locations on said work table;
  - 20 a computer capable of controlling said robotic device;  
means for inputting to said computer a set of physical dimensions and a location on said work table for said work modules;
  - 25 means for inputting to said computer a sequence of steps associated with each of said tests, each of said steps having a time of performance during which said sample must be located at the step's associated work station, said performance being completed at a step end time;
  - 30 means associated with said robotic means for coupling to a sample and capable of holding said sample during transportation between steps;
  - means for scheduling said robotic device to move a sample sequentially to the work stations associated with the test said sample is undergoing and deposit said sample at said work station until said step end time is reached;

means for scheduling the movement of each sample after the first step in the test so that it occurs while the other samples are disposed in their work stations;

means for causing said robotic device to

5 transport said samples responsive to said end times;

means for comparing the scheduled time of movement of each of said samples to determine if conflicts exist,

means for determining if multiple samples are

10 scheduled to be disposed at the same work station during the same time, and

means for adjusting the time schedule of any sample within a predetermined time range to resolve any conflicts determined by said means for comparing.

15 3. A robotic system to transport a plurality of samples, each sample undergoing a test procedure having a plurality of steps, to a plurality of work stations each associated with one of said steps wherein said samples are undergoing said test procedures substantially simultaneously, said system comprising

a multi axis robotic device having a predetermined working range area;

a work table substantially coextensive with said working range area;

25 a plurality of work modules each associated with one of said steps disposed at identifiable locations on said work table;

a computer capable of controlling said robotic device;

30 means for inputting to said computer a set of physical dimensions and a location on said work table for said work modules;

means for inputting to said computer a sequence of steps associated with each of said tests, each of said

35 steps having a time of performance during which said

sample must be located at the step's associated work station, said performance being completed at a step end time;

5 means associated with said robotic means for coupling to a sample and capable of holding said sample during transportation between steps;

means for scheduling said robotic device to move a sample sequentially to the work stations associated with the test said sample is undergoing and deposit said sample 10 at said work station until said step end time is reached;

means for scheduling the movement of each sample after the first step in the test so that it occurs while the other samples are disposed in their work stations;

means for causing said robotic device to 15 transport said samples responsive to said end times;

means for optimizing the scheduling of said device, said means for optimizing including

iteration means for producing a plurality of different schedules less than all possible schedules;

20 means for providing statistical information concerning a time distribution of said plurality of different schedules; and

means for halting said iteration and accept one of the schedules that comes close to the optimum schedule 25 based on said statistical distribution.

4. Apparatus to control the scheduling of multiple tests, each test comprising several distinct steps, each step having a predetermined range of processing time associated therewith, said apparatus comprising

30 a. means for determining a starting time and a completion time for each of the steps in the multiple tests,

b. means for scheduling the steps of said multiple tests in a single time sequence arrangement 35 interleaving the steps of said tests,

c. means for detecting time conflicts of interfering starting and completion times of said interleaved steps,

d. means for resolving said time conflicts by

5 adjusting the starting and completion times of one or more of said steps in response to said predetermined range of processing time.

5. A method for controlling a robotic system so as to simultaneously process a number of samples through a 10 variety of different assays, each assay associated with one of said samples and having one or more steps processing said associated sample at a work station, each of said steps having a predetermined range of processing time during which the sample must be located at said 15 station wherein said robotic system includes;

a. a work table defining a work area;

b. a plurality of work modules each designed to process a sample through one step of an assay and each of said modules having physical characteristics associated 20 therewith;

c. means to dispose each of said work modules within said work area;

d. means to determine the specific location of each of said modules;

25 e. a robotic device having a plurality of movement axis and means to grasp one of said samples;

f. computer means having a central processing unit;

30 g. means to control said robotic device to cause said device to grasp and transport said samples responsive to the output of said central processing unit said method comprising the steps of

1. assigning a time to start each of said assays,

2. determining a desired start time and a desired completion time for each of said steps, responsive to the start time for each of said assays and the predetermined range of processing time associated with 5. each of the steps of said assays,

3. creating a schedule time interleaving of all of said steps responsive to said start times,

4. determining the existence of interfering times therein the start or completion time of 10 one step is scheduled at the same time as the start or completion time of another step,

5. resolving, said conflicts to produce a nonconflicting schedule to perform all the steps of each of the assays in a time multiplexed manner,

15 6. reviewing and iterating the steps of this method to produce a practical optimized non-conflicting schedule,

7. providing data input to said central processing unit defining the location and physical 20 characteristics of each of said work stations,

8. creating output signals from said central processing unit to control said robotic device in accordance with said optimized schedule and input data to cause the robotic device to transport and deposit each of 25 said samples in a work station in accordance with said schedule.

6. A method of simultaneously exposing a plurality of test samples to a multiplicity of tests, each sample being subjected to one of said tests and each test having 30 a number of steps, said method comprising

a. selecting the test to which each sample is to be exposed;

b. determining the steps that compose the selected tests;

- c. ascertaining a predetermined time range for each step;
- d. scheduling all of said steps into a single program;
- 5 e. determining if time conflicts exist between steps of multiple processes;
- f. adjusting the timing of any conflicting steps by altering start or stop times in response to said predetermined time ranges;
- 10 to provide a time sequential arrangement for all the steps comprising all the tests.

7. A system for performing a plurality of independent analysis procedures simultaneously, each said procedure having a sample and at least one process step 15 for operating on that sample, said system comprising

- a robotic arm for moving the samples among a plurality of processing stations; and
- a processor for selecting, at a plurality of times, a sample to be moved, and for directing said 20 robotic arm to move said sample to be moved; said processor having means for directing said robotic arm to interleave the process steps of said plurality of independent analysis procedures;
- wherein said processor comprises
- 25 means for generating a plurality of possible sequences of process steps, less than all possible sequences;
- means for determining statistical information about a time distribution of said plurality; and
- 30 means for selecting one of said plurality with a desired total expected time, so as to substantially minimize a total time required to complete said procedures.

8. A system as in claim 7, wherein said processing stations are disposed in a set of grid locations, wherein said robotic arm is coupled to a robotic device, and wherein said robotic device comprises a bench robot with 5 a rotatable tower and with sufficient degrees of freedom that it is able to reach each of the grid locations with suitable movement.

9. A system as in claim 7, wherein said processing stations comprise workstations for performing individual 10 steps of the analysis procedures.

10. A system as in claim 7, wherein at least one said processing station comprises one of the group: a bioassay workstation, a biomedical workstation, a chemical process workstation.

15 11. A system as in claim 7, wherein said processor comprises a memory for storing a start time and an end time for each said process step.

12. A system as in claim 7, wherein said processor comprises a memory for storing timing information for each 20 said process step, said timing information comprising a range of times at which said process step may be in a predetermined state.

13. A system as in claim 7, wherein said processor comprises means for selecting said sample to be moved in 25 response to timing information about said procedures.

14. A system for performing a plurality of independent analysis procedures simultaneously, each said procedure having a sample and at least one process step for operating on that sample, said system comprising

a robotic arm for moving the samples among a plurality of processing stations; and

5 a processor for selecting, at a plurality of times, a sample to be moved, and for directing said robotic arm to move said sample to be moved; said processor having means for directing said robotic arm to interleave the process steps of said plurality of independent analysis procedures;

wherein said processor comprises

10 a memory for storing timing information for each said process step, said timing information comprising a predetermined range of durations during which said process step may be in a predetermined state; and

15 means for determining an exact time to start each said process step in a first said procedure in response to timing information for at least one process step in a second said procedure.

15. A system as in claim 14, wherein said means for determining comprises

20 means for generating a possible sequence of process steps;

means for examining said possible sequence for possible conflicts; and

25 means for altering said possible sequence in response to said timing information and said possible conflicts.

16. A system as in claim 14, wherein said means for determining comprises

means for generating a possible sequence of 30 process steps;

means for examining said possible sequence for timing conflicts occurring before a known time value;

means for advancing said known time value from a beginning of said possible sequence to an end of said possible sequence;

5 means, when a first process step is found to have a timing conflict with a second process step and said first process step has a range of times at which it may be started, for selecting an exact time to start said first process step; and

10 means, when a first process step is found to have a timing conflict with a second process step and said first and second process steps have exact times at which they may be started, for backtracking said known time value and altering said possible sequence starting from said backtracked known time value to avoid said timing 15 conflict.

17. A system as in claim 14, wherein said processor comprises

means for generating a plurality of possible sequences of process steps;

20 means for evaluating each said possible sequence for total expected time; and

means for selecting one said possible sequence with a desired total expected time, so as to minimize a total time required to complete said procedures.

25 18. A system for performing a plurality of independent analysis procedures simultaneously, each said procedure having a sample and at least one process step for operating on that sample, said system comprising

a robotic arm for moving the samples among a 30 plurality of processing stations; and

a processor for selecting, at a plurality of times, a sample to be moved, and for directing said robotic arm to move said sample to be moved; said processor having means for directing said robotic arm to

interleave the process steps of said plurality of independent analysis procedures;

wherein said processor comprises  
a display screen;

5 means for identifying a symbol shown on said display screen in response to a selection from an operator;

means for associating a process step with said symbol; and

10 means for recording an ordered sequence of said process steps.

19. A system as in claim 18, wherein said means for identifying comprises a pointing device.

20. A system as in claim 18, comprising means for 15 receiving information from said operator about the process step associated with said symbol.

21. A system as in claim 20, wherein said information comprises timing information.

22. A system as in claim 20, wherein said 20 information comprises a minimum time and a maximum time for said process step associated with said symbol.

23. A system for performing a plurality of independent analysis procedures simultaneously, each said procedure having a sample and at least one process step 25 for operating on that sample, said system comprising

a robotic arm for moving the samples among a plurality of processing stations; and

30 a processor for selecting, at a plurality of times, a sample to be moved, and for directing said robotic arm to move said sample to be moved; said processor having means for directing said robotic arm to

interleave the process steps of said plurality of independent analysis procedures;

comprising

a display screen;

5 means for drawing a new symbol on said display screen in response to information from an operator; and means for associating a processing station with said new symbol.

24. A system as in claim 23, wherein said means for 10 drawing comprises a pointing device.

25. A system as in claim 23, comprising means for receiving information from said operator about the processing station associated with said new symbol.

26. A system for performing a plurality of 15 independent analysis procedures simultaneously, each said procedure having a sample and at least one process step for operating on that sample, said system comprising a robotic arm for moving the samples among a plurality of processing stations;

20 a processor for selecting, at a plurality of times, a sample to be moved, and for directing said robotic arm to move said sample to be moved; said processor having means for directing said robotic arm to interleave the process steps of said plurality of 25 independent analysis procedures;

means for monitoring dynamic progress information for said procedures; and

means for altering a sequence of said process steps in response to said progress information and in 30 response to information from an operator.

27. A system as in claim 26, wherein said means for altering comprises

means for signalling an error when said known time value is backtracked beyond the time said altering occurs.

30. A method for performing a plurality of 5 independent analysis procedures simultaneously, each said procedure having a sample and at least one process step for operating on that sample, said method comprising the steps of

selecting, at a plurality of times, a sample to 10 be moved, said step of selecting comprising the steps of (1) generating a plurality of possible sequences of process steps, less than all possible sequences, (2) determining statistical information about a time distribution of said plurality, (3) selecting a preferred 15 one of said plurality with a desired total expected time, so as to substantially minimize a total time required to complete said procedures, and (4) selecting said sample to be moved in accordance with said preferred one of said plurality of possible sequences;

20 directing a robotic arm to move said sample to be moved by interleaving the process steps of said plurality of independent analysis procedures.

31. A method as in claim 30, comprising the step of 25 storing a start time and an end time for each said process step.

32. A method as in claim 30, comprising the step of storing timing information for each said process step, said timing information comprising a range of times at which said process step may be in a predetermined state.

30 33. A method as in claim 30, comprising the step of selecting said sample to be moved in response to timing information about said procedures.

34. A method as in claim 30, comprising the steps of  
storing timing information for each said process  
step, said timing information comprising a predetermined  
range of durations during which said process step may be  
5 in a predetermined state; and

determining an exact time to start each said  
process step in a first said procedure in response to  
timing information for at least one process step in a  
second said procedure.

10 35. A method as in claim 34, wherein said step of  
determining comprises the steps of  
generating a possible sequence of process steps;  
examining said possible sequence for possible  
conflicts; and

15 altering said possible sequence in response to  
said timing information and said possible conflicts.

36. A method as in claim 34, wherein said step of  
determining comprises the steps of  
generating a possible sequence of process steps;  
20 examining said possible sequence for timing  
conflicts occurring before a known time value;  
advancing said known time value from a beginning  
of said possible sequence to an end of said possible  
sequence;

25 selecting an exact time to start said first  
process step when a first process step is found to have a  
timing conflict with a second process step and said first  
process step has a range of times at which it may be  
started; and

30 backtracking said known time value and altering  
said possible sequence starting from said backtracked  
known time value to avoid said timing conflict when a  
first process step is found to have a timing conflict with

a second process step and said first and second process steps have exact times at which they may be started.

37. A method as in claim 34, comprising the steps of generating a plurality of possible sequences of 5 process steps; evaluating each said possible sequence for total expected time; and

second process step and said first and second process steps have exact times at which they may be started; and signalling an error when said known time value is backtracked beyond the time said altering occurs.

5 51. In a system for performing a plurality of independent analysis procedures simultaneously, each said procedure having a sample and at least one process step for operating on that sample, a data structure comprising an entry for each one of a plurality of process steps, 10 each said entry comprising a predetermined range of times at which said process step may be in a predetermined state.

15 52. In a system for performing a plurality of independent analysis procedures simultaneously, each said procedure having a sample and at least one process step for operating on that sample, a data structure comprising a sequence of process steps indexed by a time value and indicating a start time and an end time for each said process step.

20 53. A data structure as in claim 52, comprising a second sequence of process steps indexed by said time value, wherein said second sequence comprises process steps from a single procedure.

25 54. In a system for performing a plurality of independent analysis procedures simultaneously, each said procedure having a sample and at least one process step for operating on that sample, a data structure comprising an ordered sequence of entries, each said entry comprising a symbol on a display screen and a process step.

30 55. A data structure as in claim 54, wherein each entry comprises timing information for said process step.

56. A system for performing a plurality of independent analysis procedures simultaneously, each said procedure having a sample and at least one process step for operating on that sample, said system comprising

5 a robotic arm for moving the samples among a plurality of processing stations;

10 a processor for selecting, at a plurality of times, a sample to be moved, and for directing said robotic arm to move said sample to be moved; said processor having means for directing said robotic arm to interleave the process steps of said plurality of independent analysis procedures;

15 means for monitoring progress information for said procedures; and

20 means for altering a sequence of said process steps in response to said progress information and in response to information from an operator.

25 wherein said means for altering comprises (1) means for generating a possible new sequence of process steps from a time said altering occurs onward, (2) means for examining said possible new sequence for possible conflicts, and (3) means for altering said possible new sequence in response to said timing information and said possible conflicts.

25 57. A system for performing a plurality of independent analysis procedures simultaneously, each said procedure having a sample and at least one process step for operating on that sample, said system comprising

30 a robotic arm for moving the samples among a plurality of processing stations;

35 a processor for selecting, at a plurality of times, a sample to be moved, and for directing said robotic arm to move said sample to be moved; said processor having means for directing said robotic arm to

interleave the process steps of said plurality of independent analysis procedures;

means for monitoring progress information for said procedures; and

5 means for altering a sequence of said process steps in response to said progress information and in response to information from an operator.

wherein said means for determining comprises (1) means for generating a possible new sequence of process 10 steps from a time said altering occurs onward, (2) means for examining said possible new sequence for timing conflicts occurring before a known time value, (3) means for advancing said known time value from the time said altering occurs an end of said possible new sequence, (4) 15 means, when a first process step is found to have a timing conflict with a second process step and said first process step has a range of times at which it may be started, for selecting an exact time to start said first process step, (5) means, when a first process step is found to have a 20 timing conflict with a second process step and said first and second process steps have exact times at which they may be started, for backtracking said known time value and altering said possible new sequence starting from said backtracked known time value to avoid said timing 25 conflict, and (6) means for signalling an error when said known time value is backtracked beyond the time said altering occurs.

58. A method for performing a plurality of independent analysis procedures simultaneously, each said 30 procedure having a sample and at least one process step for operating on that sample, said method comprising the steps of

selecting, at a plurality of times, a sample to be moved;

directing a robotic arm to move said sample to be moved by interleaving the process steps of said plurality of independent analysis procedures;

5 monitoring progress information for said procedures; and

altering a sequence of said process steps in response to said progress information and in response to information from an operator.

wherein said step of altering comprises the  
10 steps of (1) generating a possible new sequence of process steps from a time said altering occurs onward, (2) examining said possible new sequence for possible conflicts, and (3) altering said possible new sequence in response to said timing information and said possible  
15 conflicts.

59. A method for performing a plurality of independent analysis procedures simultaneously, each said procedure having a sample and at least one process step for operating on that sample, said method comprising the  
20 steps of

selecting, at a plurality of times, a sample to be moved;

25 directing a robotic arm to move said sample to be moved by interleaving the process steps of said plurality of independent analysis procedures.

monitoring progress information for said procedures; and

altering a sequence of said process steps in response to said progress information and in response to  
30 information from an operator.

wherein said step of determining comprises the steps of (1) generating a possible new sequence of process steps from a time said altering occurs onward, (2) examining said possible new sequence for timing conflicts  
35 occurring before a known time value, (3) advancing said

known time value from the time said altering occurs an end of said possible new sequence, (4) selecting an exact time to start said first process step when a first process step is found to have a timing conflict with a second process  
5 step and said first process step has a range of times at which it may be started, (5) backtracking said known time value and altering said possible new sequence starting from said backtracked known time value to avoid said timing conflict when a first process step is found to have  
10 a timing conflict with a second process step and said first and second process steps have exact times at which they may be started, and (6) signalling an error when said known time value is backtracked beyond the time said altering occurs.

15 60. A system as in claim 7, comprising means for halting the operation of said means for generating in response to said plurality of possible sequences and said statistical information.

61. A system as in claim 7, comprising means for  
20 halting the operation of said means for generating when said total expected time of one of said plurality is close to a total expect time computed in response to said statistical distribution.

## STATEMENT UNDER ARTICLE 19

In a first aspect, the invention includes a system which can perform a plurality of independent analysis procedures simultaneously, for example by interleaving the differing process steps. The interleaving is accomplished by examining a set of sample sequences of process steps, less than all possible combinations, and selecting the best available sequence from the examined set. By examining only a statistical sample of sequences, the processor is able to select an interleaving sequence quickly, thus is able to alter the selected sequence dynamically in response to new information.

Isenhour specifically searches the "entire solution space" (p. 217, last paragraph), depth-first, and selects a solution, i.e., an ordering of tasks, which takes the minimal amount of time. The amount of time required to generate and search the entire solution space is quite large, so Isenhour has no reasonable method by which tasks may be reordered, added, deleted, or otherwise manipulated, dynamically. In contrast, the present invention is able to select a good solution (based on its sample of the solution space) in quick order, and it thus able to modify the task list dynamically.

In a second aspect of the invention, each process step may be given a range of allowable durations, i.e., a minimum and a maximum allowable duration, which the interleaving processor may use when attempting to construct sample sequences. Because each process step may be longer or shorter than the optimal time, the processor is able to fit the process steps together into more interleaved sequences. This allows the processor to find more sample sequences which take less total time to execute.

Isenhour specifically requires each process step to take its fixed amount of time, plus any "slack time". "Slack time" is specifically defined based on critical path analysis (p. 217), and can only be computed based on the critical path which is then known by Isenhour's system. This is quite different from the invention, in that minimum and maximum times for each process step are predetermined, and represent differing amounts of time the process step may take chemically. For example, in the invention, a step may be

specified as taking as little as 1 minute or as much as 3 minutes, without substantial effect on the chemical operation.

In a third aspect of the invention, an operator may specify the steps of a procedure using a graphic interface, which may include a display of grid locations for workstations, and a list of process steps for a procedure. The operator may also monitor the progress of ongoing procedures, override the determination of what process steps to perform, and add new procedures as older ones are being performed.

The art cited does not show or suggest graphical inspection of locations (where workstations are deployed) at the same time and with the same tools as graphical inspection of timing (when process steps are performed). In fact, Isenhour's TORTS system teaches against this combination because it shows that all workstations are in fixed locations.

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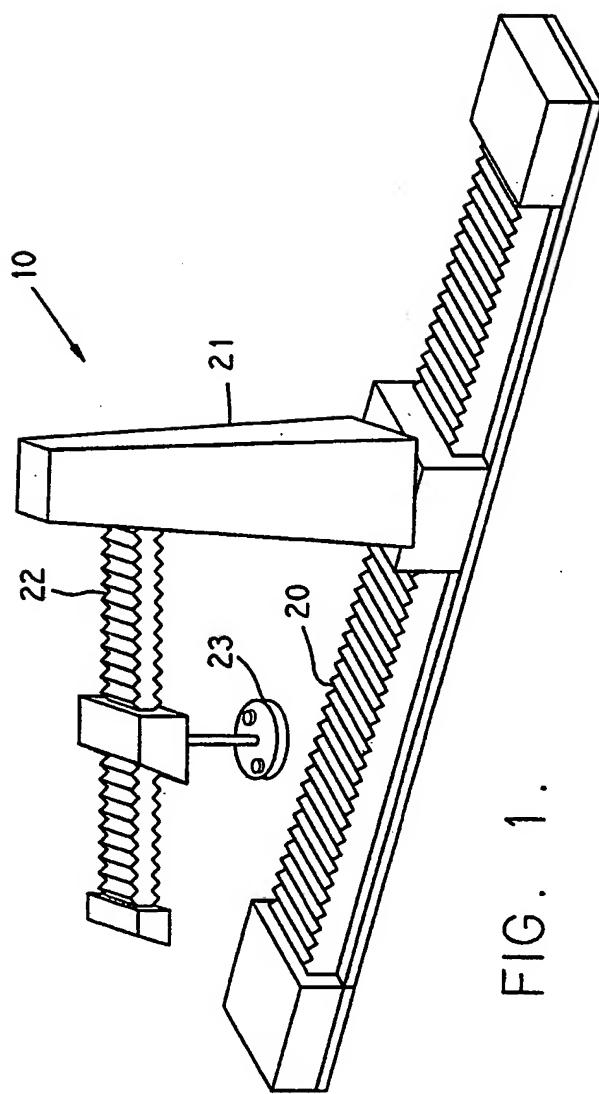


FIG. 1.

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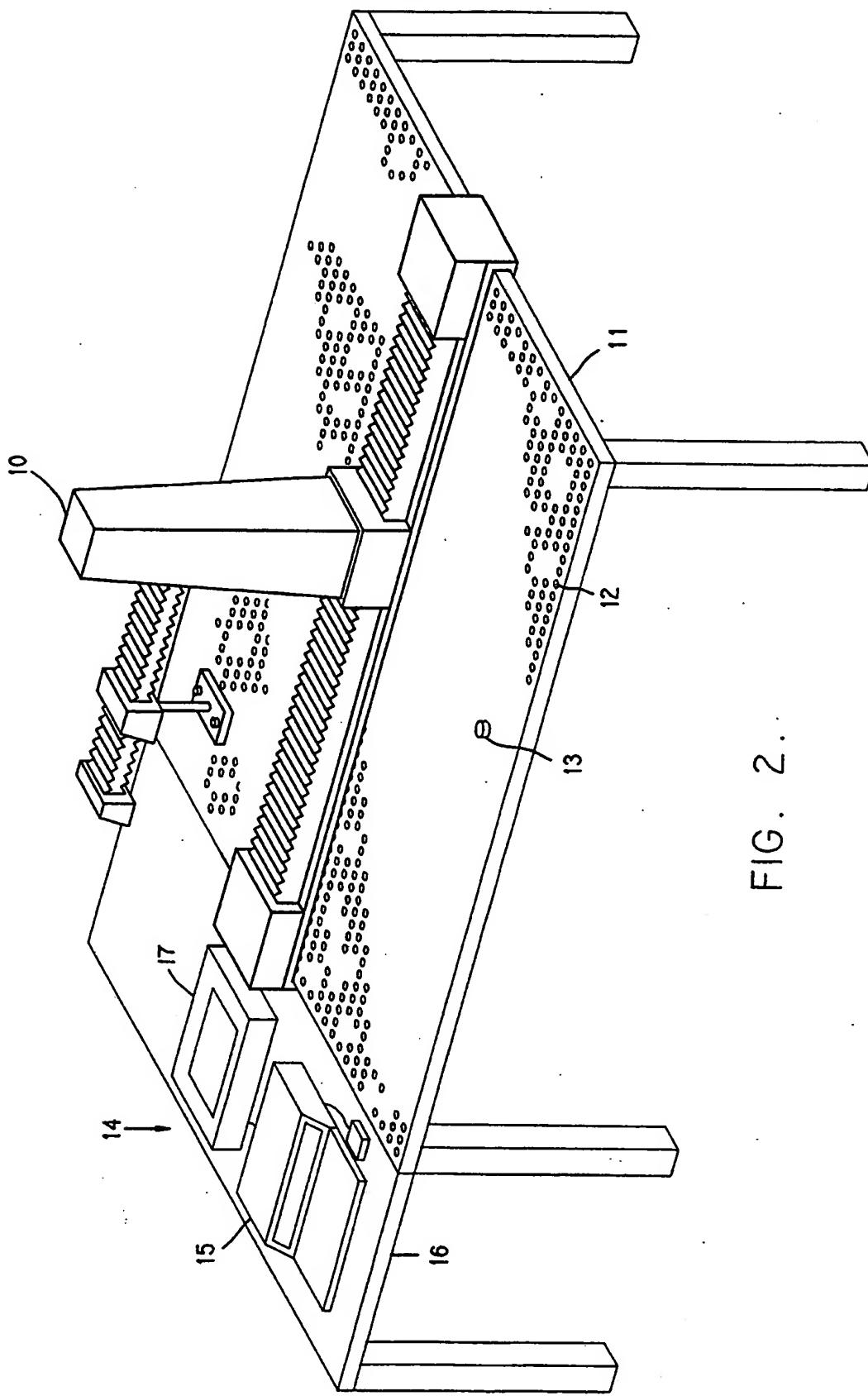


FIG. 2.

SUBSTITUTE SHEET

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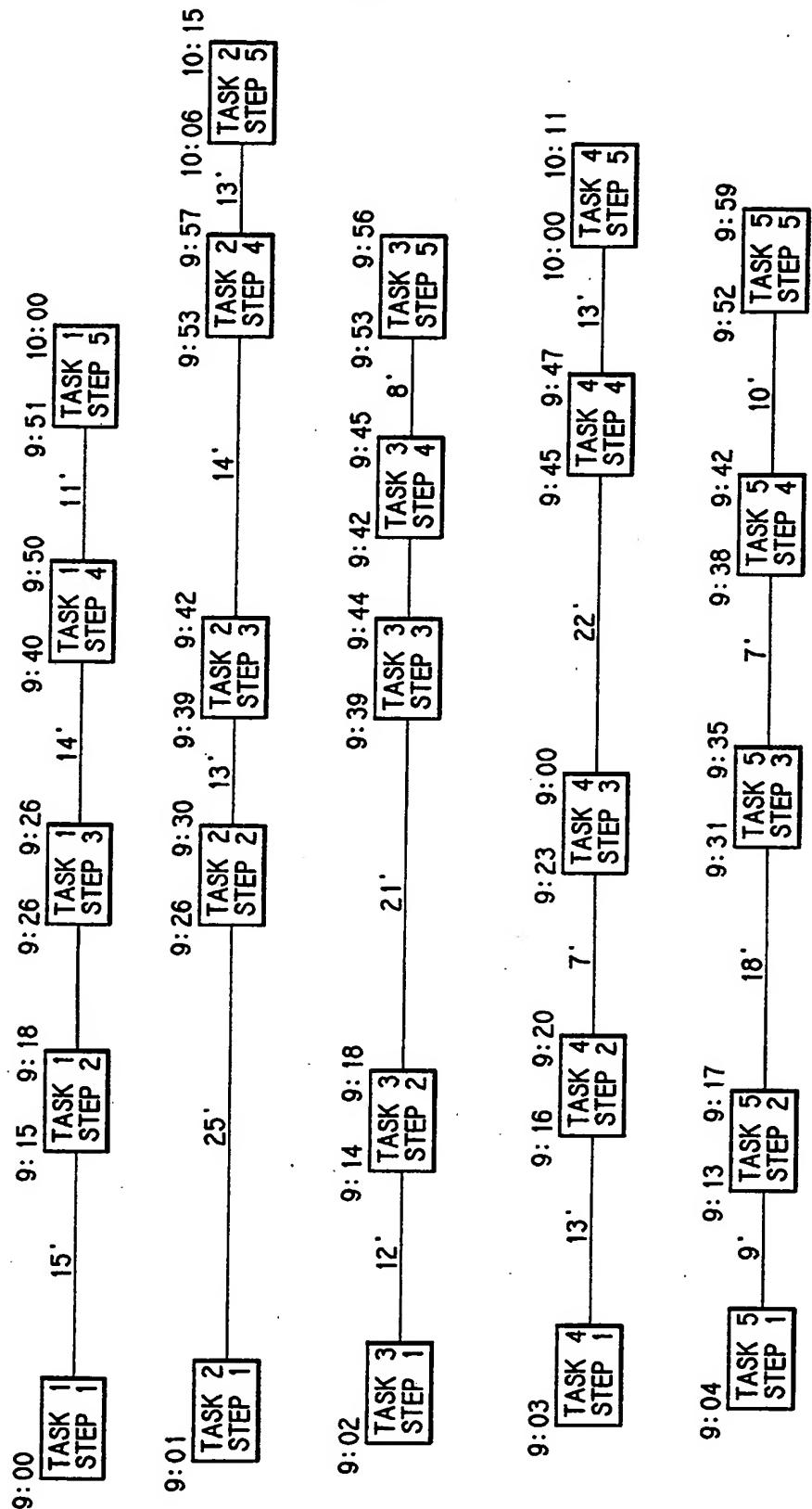
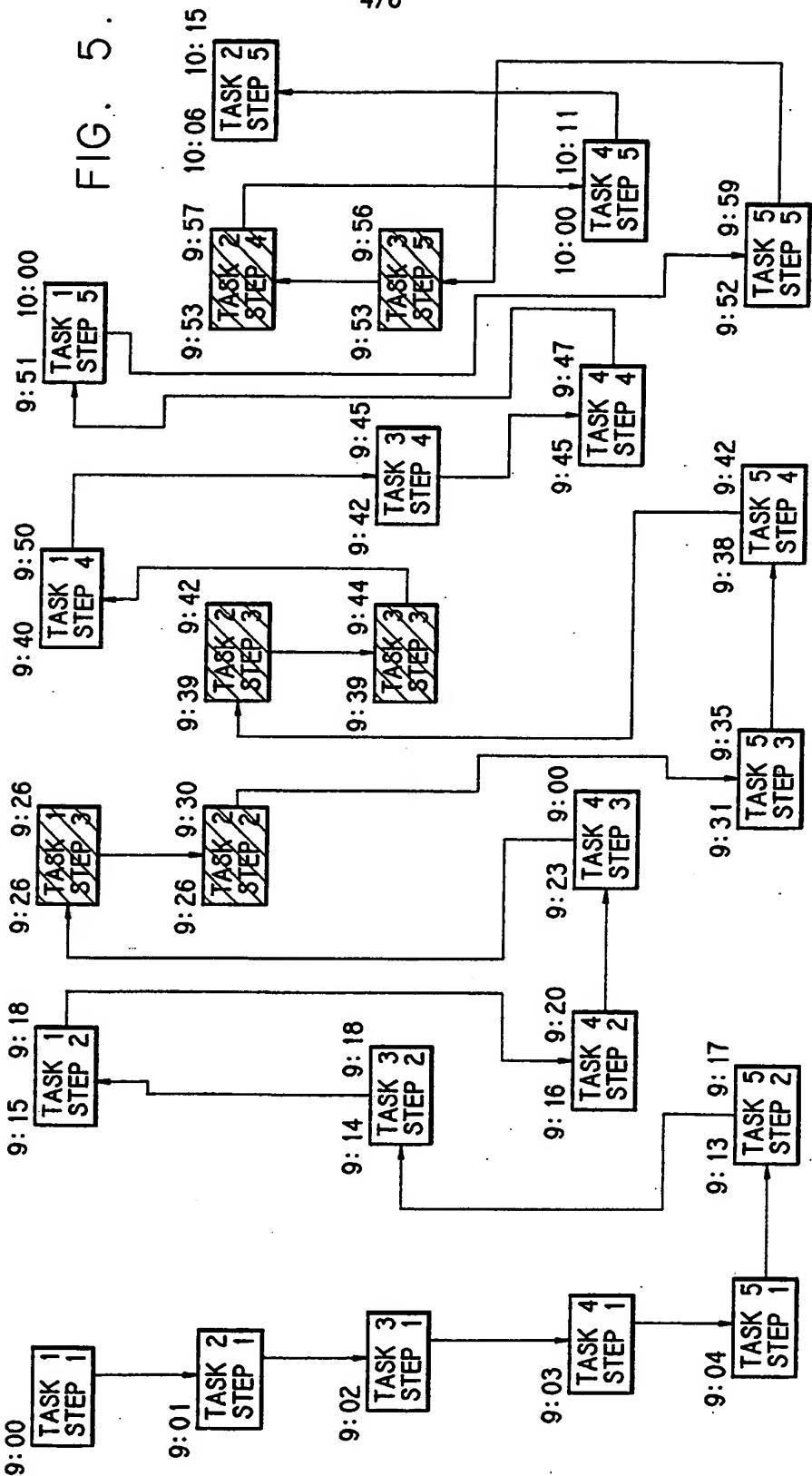


FIG. 4.

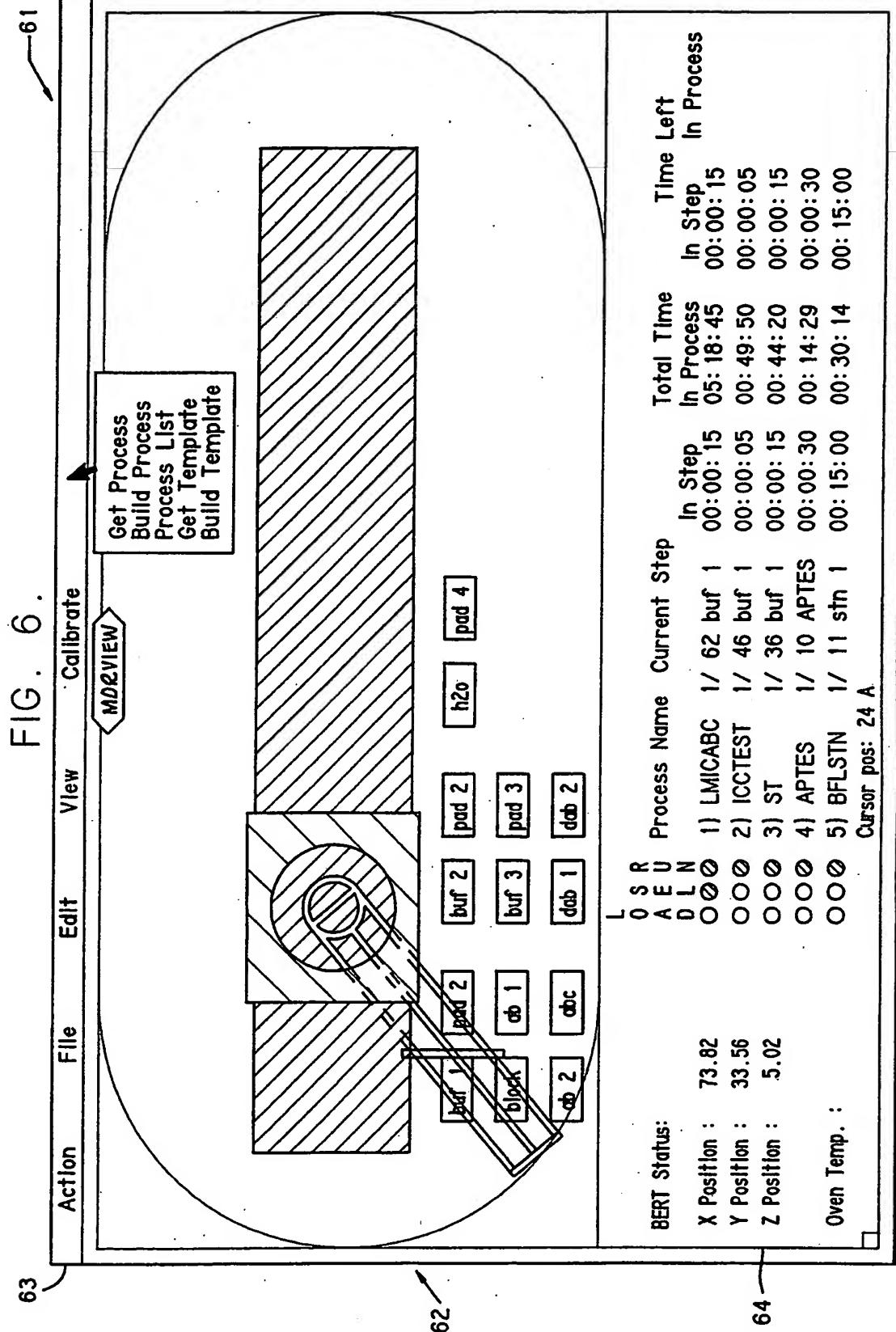
SUBSTITUTE SHEET

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SUBSTITUTE SHEET

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二十一

FIG. 7.

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### BERT Status:

D L N      1) LMICABC  
 40 0 0 0      1) ICCTEST  
 30 0 0 0      2) 3)  
 0 0 0 0      4) APTES  
 500 0 0 0

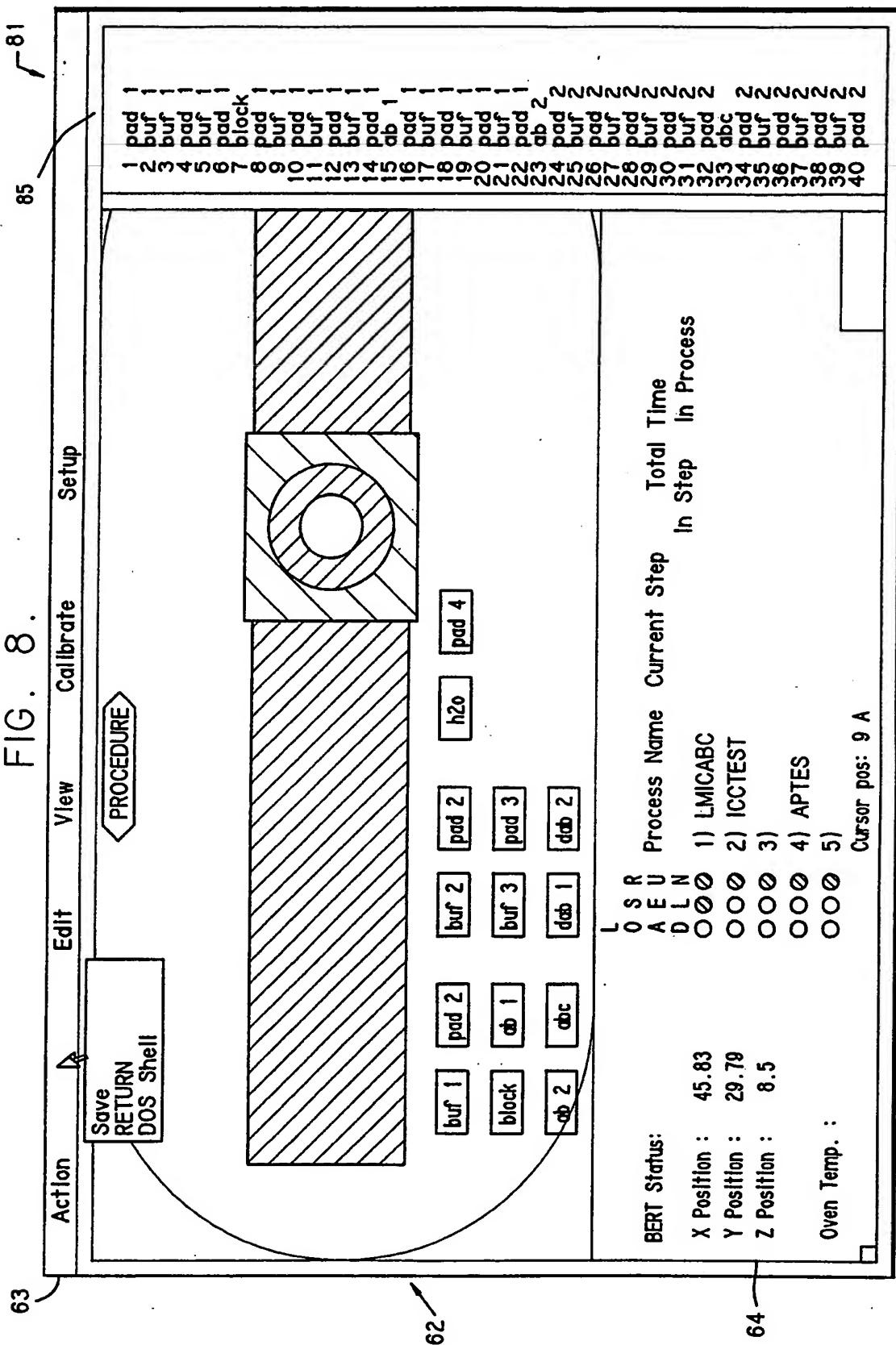
Cursor pos: 29 A

pad 4

## **SUBSTITUTE SHEET**

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8.  
E



## **SUBSTITUTE SHEET**

FIG. 9.

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Action	File	Edit	View	Calibrate	Setup	PROCESS LIST	VIEW
Step No.	Step	Name	Min Time	Max Time	Time	Yes/No/Hold	
1	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
2	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
3	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
4	buf	block	00: 00: 30	00: 00: 30	00: 00: 30	Yes	
5	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
6	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
7	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
8	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
9	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
10	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
11	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
12	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
13	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
14	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
15	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
16	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
17	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
18	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
19	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
20	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
21	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
22	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
23	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
24	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	
25	buf		00: 00: 15	00: 00: 30	00: 00: 15	Yes	

✓ 92

✓ 93

✓ 94

✓ 95

✓ 96

✓ 97

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US92/06478

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :G06F 15/46

US CL :395/82

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 395/82

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Dialog: Robot/Robotic, Schedule/Scheduling, Optimization, Laboratory

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 4,727,494 (BUOTE) 23 FEBRUARY 1988	
X Y	Journal of Chemical Information and Computer Sciences; Nov. 1988; Isenhour, T. L., Harrington, P. B.; TORTS: An Expert System for Temporal Optimization of Robotic Procedures; 215-221.	1-27, 30-41, and 51-55 42-48
A	Journal of Chemical Information and Computer Sciences, 1985; Isenhour, T. L.; Robotics in the Laboratory; 292-295.	

 Further documents are listed in the continuation of Box C. See patent family annex.

Special categories of cited documents:			
"A"	document defining the general state of the art which is not considered to be part of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"Z"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search  
02 SEPTEMBER 1992

Date of mailing of the international search report

16 OCT 1992

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